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DEVELOPMENT OF A RULE-BASED STRUCTURAL DAMAGE ASSESSMENT CODE

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This research effort uses expert system techniques in the damage assessment of buried protective structures. An expert system approach was chosen for this study because much of the information used in the damage assessment process is obtained from engineering judgment and therefore involves linguistic interpretation of vague or uncertain terminology and ideas.

The development of this damage assessment code is based on a series of ~~11~~ 9 tests conducted ~~in 1981 and 1982~~ on 1/4-scale reinforced concrete boxes. The box elements in these tests were subjected to simulated high explosive blast loads and thus sustained large amounts of damage.

Both subjective and objective information are used in this study. The subjective information was derived from a questionnaire sent to experts around the country concerning the levels of damage and modes of response in the experimental tests. Because the knowledge obtained from the experts contained ambiguous and uncertain terminology, the theory of fuzzy sets (over)

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To convert from	To	Multiply by
inch (in)	millimeter (mm)	25.4
foot (ft)	meter (m)	0.3048
pound (lb)	kilogram (kg)	0.453 592
pound/square inch (lb/in^2, psi)	kilopascal (kPA)	6.894 76
kip/square inch (k/in^2, ksi)	megapascal (MPa)	6.894 76

I. INTRODUCTION

PROBLEM STATEMENT

The military forces of the United States use a great number of shallow-buried reinforced concrete protective structures for a variety of purposes. As such, information used in estimating or determining the survivability and vulnerability (S/V) of these structures is needed to evaluate structural safety and reliability. The quantity of data available on which to base a study of the responses of shallow-buried structures to blast effects is very limited. Thus, the investigation into the S/V of these buried structures has depended primarily on conventional explosive airblast simulation techniques in order to develop a data base.

Figure 1 is a scaled representation of the shallow buried structure problem. Again, the issue in this problem is the ability to estimate the survivability of the buried box to the conditions imposed by an extreme environment, such as those induced by an impulsive blast load. If we take a closer look at the S/V problem definition, we see that the idea of S/V analysis involves the question: How well will the structure continue to function (survive) in a blast environment? By studying this question, we begin to envision the difficulty of the analysis process. For instance, how does one go about applying engineering quantities to such terms as "functionality remains good," or "poor blast resistance," which obviously involve degrees or levels of information that are subject to opinion.

The problem is complicated by the fact that the information needed to make an estimate with high confidence is incomplete and involves many uncertainties. Evaluation of the situation becomes even more difficult when one realizes that the uncertainties encountered include both random and nonrandom kinds of data. For instance, very little is known about the effects of modern weapons on an operational facility which is occupied by people, and which contains sensitive, technologically complex equipment. Uncertainties such as ambiguities in explosive effects, variability in material behavior, and threat scenario could be classified as random uncertainties. On the other hand, linguistic data, subjective judgment, and imprecise information are

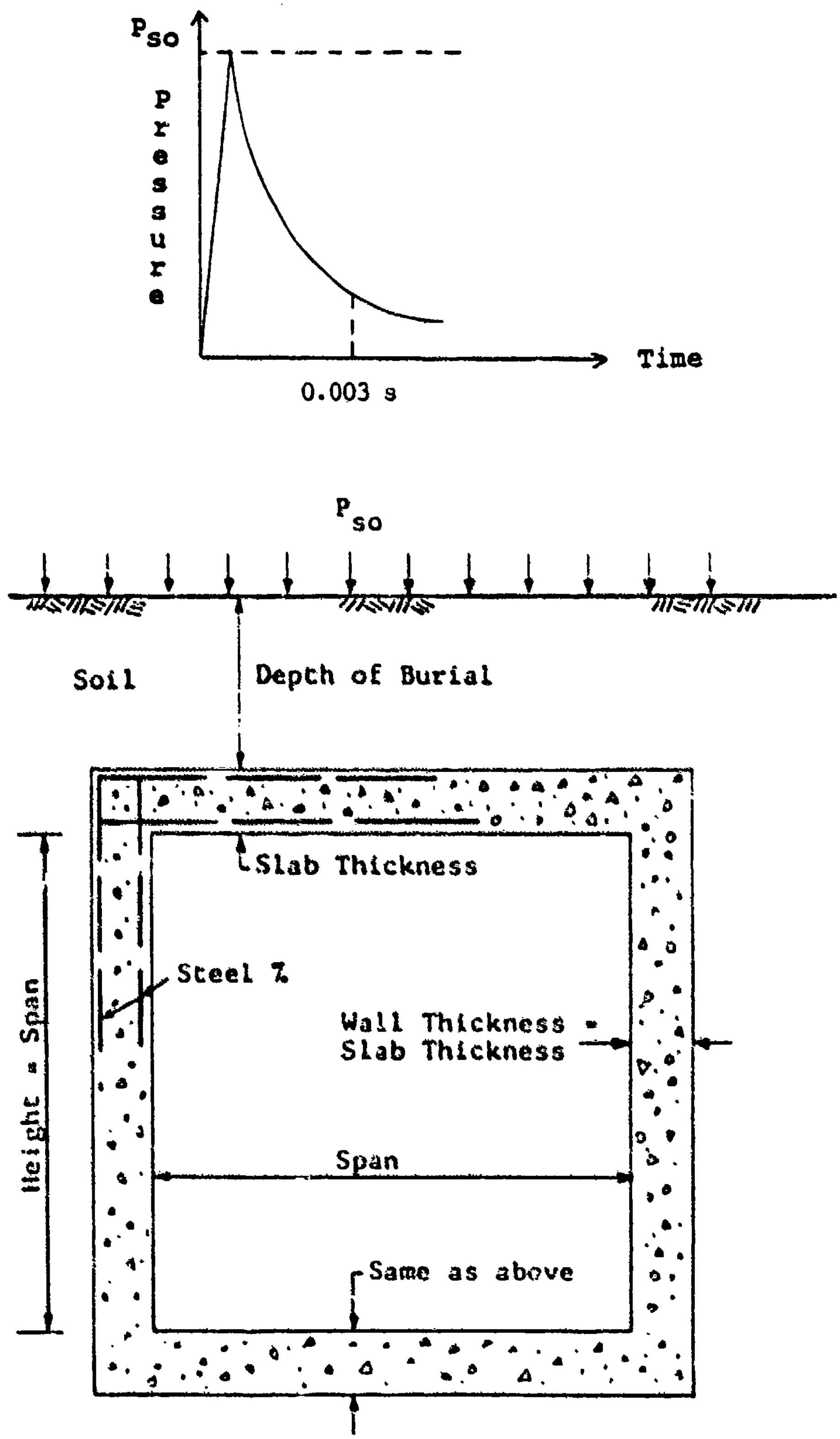


Figure 1. Shallow buried protective structure.

typical examples of nonrandom uncertainties for which the sample space is not well defined and the mean and variance are not meaningful.

From the previous discussion, we conclude that the assessment of damage to any structure, from any extreme disturbance (blast/shock, wind, earthquake, etc...) is a difficult process in which human judgment plays an important role. This is especially true of protective structures. They are usually heavily reinforced and yet may be subjected to very severe if not total failure levels. Therefore, because of its inherent dissimilarity with typical civil-engineering-type problems, we cannot rely on past experience in the area of damage assessment with any confidence.

Because of a lack of complete understanding of the real problem, in the past the typical analysis of the damaged structure would simply be assigned to one of two groups -- survival or failure. If we take a closer look at the problem, however, we see that it is not a two-class problem, but a continuous one. To illustrate, a damaged element in a protective structure is shown in Figure 2. The evaluation for slight, moderate, and severe damage differs among experts; but, more importantly, there is overlap between different levels. It is this lack of crispness (or inherent fuzziness) in the problem that causes difficulty; first, in determining the damage level, and second, in deciding on an acceptable level of damage.

Even when we assume several gray levels between no damage and total failure, there exists possibilities for misinterpretation. The reason for this is that the process of damage assessment is a cause and effect analysis. The "cause" usually involves engineering quantities (overpressures, etc...), while the "effect" involves less crisp subjective information in the areas of functionality and repairability of the structure. In other words, no matter what the cause of the damage, the resulting damage level chosen is susceptible to varying expert opinion and is highly dependent on the particular observer. Subjective information of this type resides in the minds of experts who have, over time, accumulated much experience as to the effects a given loading would produce. And, although there is objective information available to the expert (engineer or scientist) in the form of test data and model simulations, the question of survivability resides in the minds of the experts. Thus the quality of the assessment process is highly dependent on an expert's knowledge of the actual situation under study.

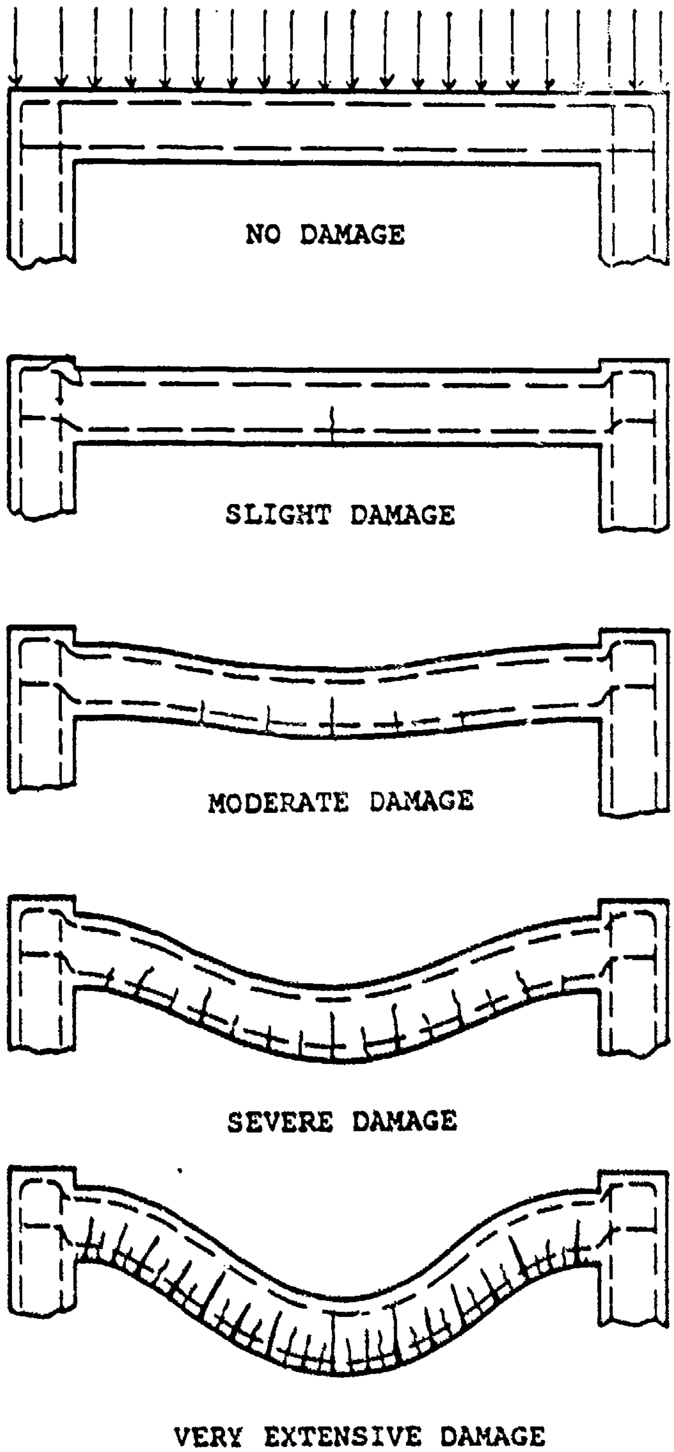


Figure 2. Linguistic descriptions of various levels of damage (modified from Ref. 1).

OBJECTIVES AND SCOPE

The discussion in the previous section was provided in order to introduce the reader to the overall problem of S/V assessment. From this discussion, it can be concluded that the process of damage assessment can be divided into two subsets: damage descriptors and damage levels. Damage descriptors may be either numerical engineering quantities or subjective linguistic information; in either case, they are used to describe the second subset. Damage levels, on the other hand, involve such concepts as structural integrity, functionality, and repairability of the structure and the degrees to which they have been affected. The purpose of this report is to study the feasibility of incorporating the information outlined above into a damage assessment code in the form of a rule-based expert system. The title of this expert system has been designated DAPS, which stands for Damage Assessment of Protective Structures.

More specifically, the objective of this report is to develop a framework by which the concepts and information developed previously may be converted to a working computer code. This framework is to include the coding of information whether it be in the form of expert opinion, engineering judgment, digital waveforms, etc..., and to develop a method for the efficient retrieval of this information for use in an expert system. The expert system will combine numeric as well as nonnumeric information and will employ the recent theory of fuzzy set logic to quantify, combine, and interpret linguistic damage descriptors.

In a broader sense, this work is part of a much larger project in which the Air Force is attempting to improve the methods and procedures used within the field of information management. In particular, the Air Force is interested in improving five specific areas related to structural dynamic tests: test design, data acquisition, data processing, data analysis, and data storage. The scope of the work in this report falls into the category of data analysis. Uses envisioned for the expert system which is developed include the following: design, prediction, diagnosis, and interpretation, as well as a training aid for engineers new to the field.

SUMMARY

In order to make this project manageable, the scope of work was narrowed to include only one specific case of the protective structure scenario. In particular, the data base for this study comes from a series of eleven experimental tests which were performed on buried reinforced concrete boxes subjected to explosive pressures. The knowledge base for this work comprises crisp data in the form of instrumentation waveforms and linguistic data obtained from experts through questionnaires based on the eleven tests. Measured data come from active or passive measurements and can be considered as hard (objective) data. Visual images and linguistic assessments from expert opinion form what will be called the soft (subjective) data. The term "soft data" is chosen since it is subject to individual judgment and not readily quantifiable (even though it may contain substantial information pertaining to the problem).

In Section II the eleven tests representing the knowledge base will be reviewed. The objective and subjective information outlined above will be thoroughly examined in Section III along with the procedures used to obtain and evaluate them. In Section IV, introductory material on expert systems and fuzzy logic will be discussed. The procedures used to aggregate and combine the information described in Section III will also be presented, along with the structure of the DAPS code. Section V contains an example session using DAPS. Finally, Section VI contains a summary and the conclusions of the work performed in association with this report, along with recommendations for future work.

II. THE BURIED BOX STRUCTURE

EXPERIMENTAL TEST SERIES BACKGROUND

Experimental work on reinforced concrete structural elements subjected to short-duration impulsive loading is limited (Ref. 2). The lack of experimental data and the need for improving current S/V analysis procedures of shallow buried structures (SBS) led to the creation of the SBS Test Program at the US Army Engineers Waterways Experiment Station (WES) in Vicksburg, Mississippi in 1978.

The SBS program was initiated at WES in order to determine the magnitude of the overpressure that would cause collapse of a structure. Since 1978, the WES has tested 89 one-way slab and box structures subjected to dynamic loads. All test programs were associated with the investigation of the behavior of flat-roofed, shallow buried structures subjected to short duration (less than 3 ms), high overpressure (greater than 2000 lb/in^2) loads. By compiling the information obtained from these tests (design parameters, analytical results, and test results), a common structured data base could be established for use in characterizing concrete slab behavior under severe loading conditions.

Early tests demonstrated that the ability of these structures to resist highly impulsive loads was normally controlled by the response of the roof slab, and that, typically, the slab failed in a flexural mode. More interestingly, however, it was found that direct shear failures could be induced in the structure by a sufficiently high overpressure which had a very short rise time and duration.

Observations of structural failures resulting from the Foam HEST (High Explosive Simulation Technique) Test Series (Ref. 3) established the need to develop dynamic shear failure criteria. Thus, a series of eleven tests, sponsored by the Department of Defense, was conducted in 1981 and 1982 on one-way reinforced concrete box structures. The objective of these experiments was to investigate possible shear failures resulting from highly impulsive, uniformly distributed pressures. Of particular interest in these tests was the response of the roof element (length-to-depth ratios between 7 and 10) of the box structure near the walls (i.e., regions of high shear stress). Also of interest in these tests was the ductility of the structure associated with

dynamic shear failures and the ability to document the response of the structure with high-speed photography.

TEST DESCRIPTION AND CONFIGURATION

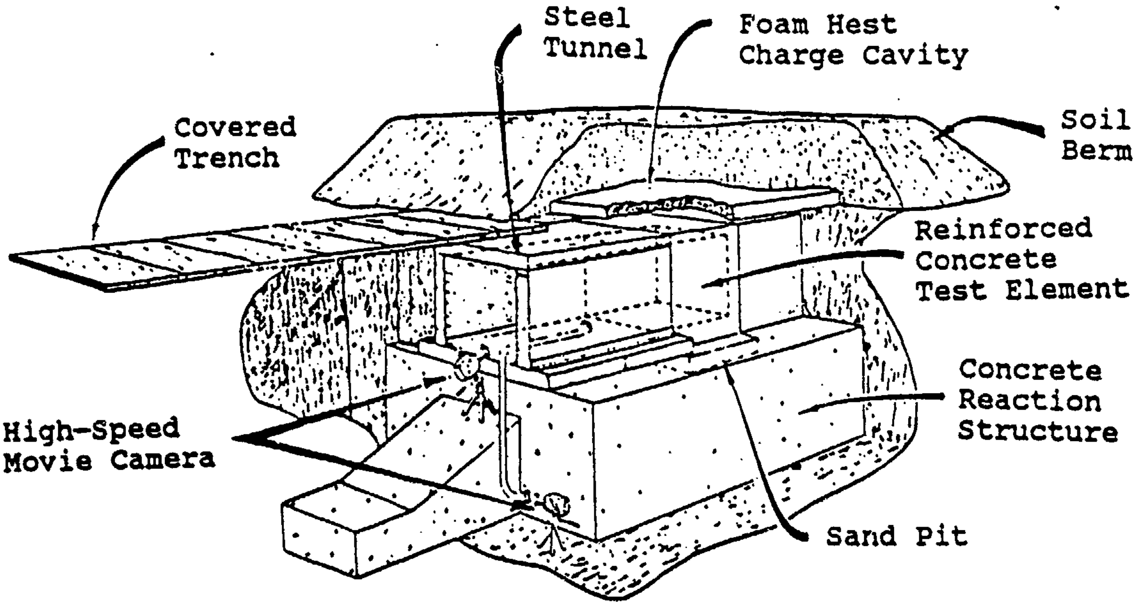
The eleven dynamic shear tests were conducted using 1/4-scale reinforced concrete box structures with no end walls. The configuration for the tests conducted at the WES is shown in Figure 3. As can be seen in Figure 3b, each of the test elements was placed in a buried reaction structure and then covered with a shallow layer of soil. A foam HEST charge cavity was placed between the soil berm and the soil covering the concrete structure. When detonated, this HEST charge provided the high-intensity blast pressure to the test specimen.

The eleven tests are categorized into three groups as shown in Tables 1 and 2. The first group is composed of the five tests conducted in 1981, while the second and third groups are composed of the six tests conducted in 1982. Each of the tests was identified by a consistent system of notation. The 1981 tests were given the designations DS1 thru DS5, while the 1982 tests were designated DS2-1 thru DS2-6. As all information and data relating to these tests is labeleo in this manner, this same notation is adopted in this report.

All elements in the test series were similarly designed and constructed. Dimensions and reinforcement patterns were the same in all roofs, walls, and floors and are shown in Figure 4. The slabs had equal percentages of tension and compression reinforcement and contained closely spaced stirrups throughout.

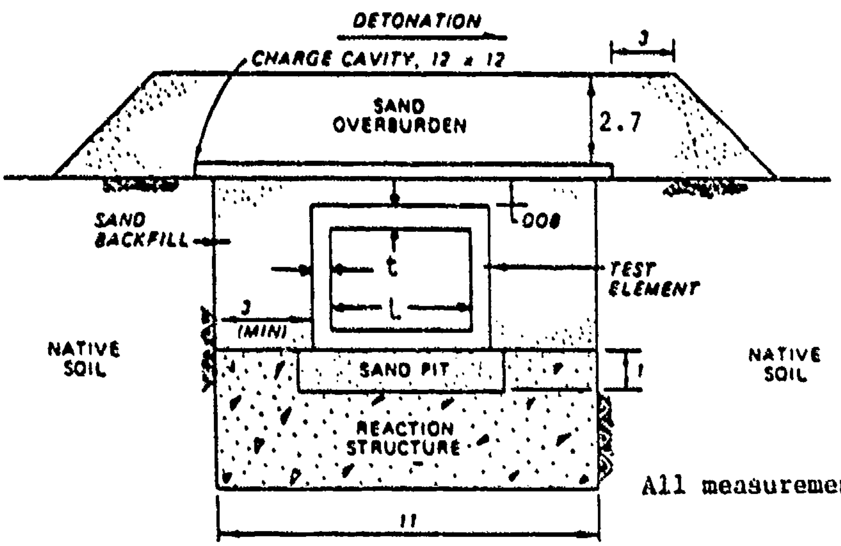
The major variations among the groups of tests were the span-to-thickness ratio and the reinforcing ratio. Properties that did not vary within test groups included overall dimensions, fabrication scheme, soil cover depth, design concrete strength, and design steel strength. Material and geometrical properties for each of the tests are listed in Tables 1 and 2, respectively. Note that the concrete strengths were denoted as averages of cylinder strengths at or near the date of testing.

Although the design load (charge density) was the same for some of the tests, variations among the tests included peak pressure along the slab, rise time to peak pressure, and decay characteristics of the pressure pulse. Load parameters for each of the tests are shown in Table 3.



Note: Fiber optics not included in FY 82 test.

(a) Three-dimensional view.



All measurements in feet.

(b) End view.

Figure 3. Dynamic shear test configuration (Ref. 2).

TABLE 1. DYNAMIC SHEAR TEST MATERIAL PROPERTIES

Element	Group	f'_c, lb/in^2	f_y, lb/in^2	f_U, lb/in^2	ν	Density, $lb\ s^2/in^4$	G, lb/in^2	Backfill	∅
DS1	1	3900	63000	102000	0.2	.2247E-3	1700000	Sand	35.5
DS2	1	3900	"	"	"	"	"	"	"
DS3	1	4000	"	"	"	"	"	"	"
DS4	1	5900	"	"	"	"	"	"	"
DS5	1	6000	"	"	"	"	"	"	"
DS2-1	2	7000	80000	119000	"	"	2000000	"	"
DS2-2	2	7700	"	"	"	"	"	"	"
DS2-3	2	7500	"	"	"	"	"	"	"
DS2-4	3	7400	67000	107000	"	"	"	"	"
DS2-5	3	7800	"	"	"	"	"	"	"
DS2-6	3	7300	"	"	"	"	"	"	"

TABLE 2. DYNAMIC SHEAR TEST GEOMETRICAL PROPERTIES

Element	Group	L, in	t, in	L/t	DOB	d, in	d', in	ρ, %	ρ', %	s/t	S_s/t	ρ_s, %
DS1	1	48.00	5.60	8.6	L/5	4.8	0.8	1.0	1.0	0.71	0.71	1.5
DS2	1	"	"	"	"	"	"	"	"	"	"	"
DS3	1	"	"	"	"	"	"	"	"	"	"	"
DS4	1	"	"	"	"	"	"	"	"	"	"	"
DS5	1	"	"	"	"	"	"	"	"	"	"	"
DS2-1	2	44.75	7.25	6.2	"	6.44	0.8	0.75	0.75	0.55	0.22	0.5
DS2-2	2	"	"	"	"	"	"	"	"	"	"	"
DS2-3	2	"	"	"	"	"	"	"	"	"	"	"
DS2-4	3	"	"	"	"	"	"	1.20	1.20	"	"	"
DS2-5	3	"	"	"	"	"	"	"	"	"	"	"
DS2-6	3	"	"	"	"	"	"	"	"	"	"	"

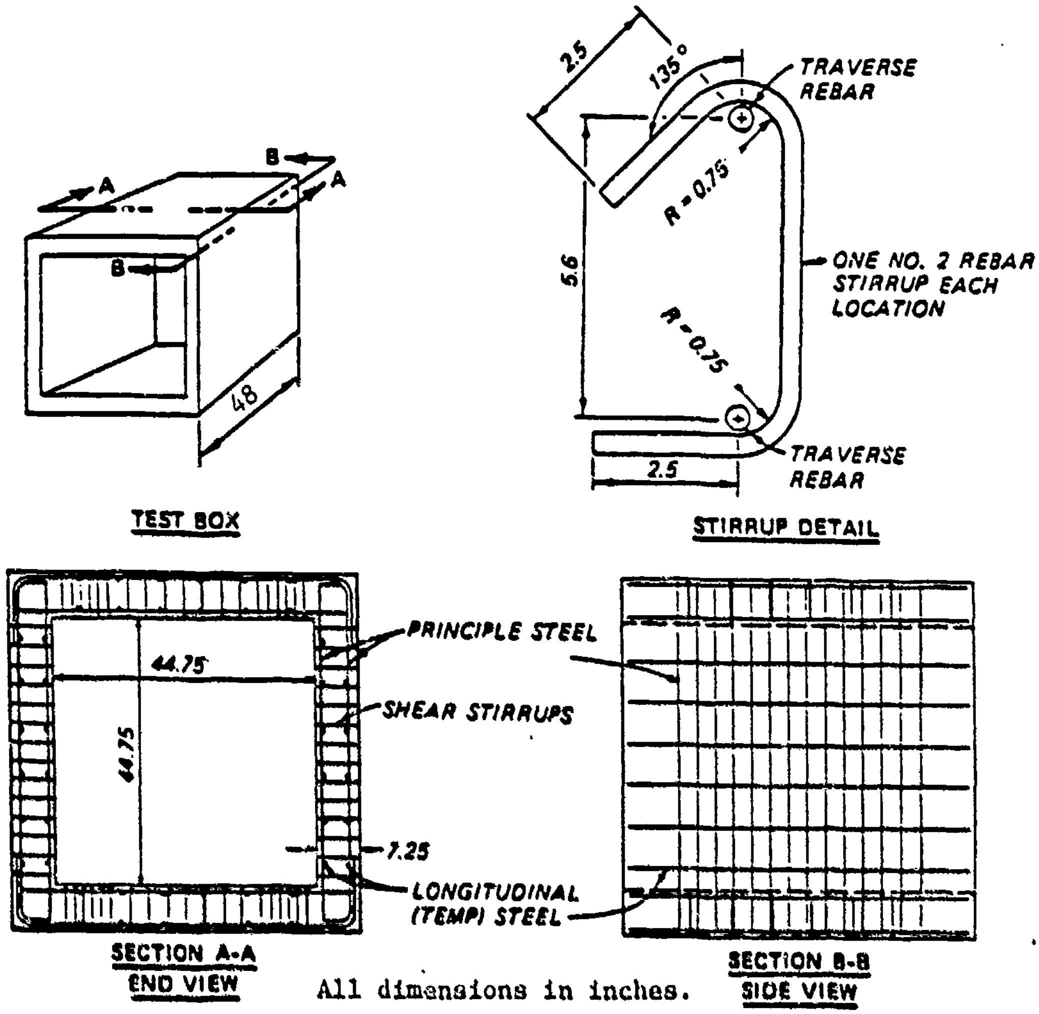


Figure 4. Test element construction details, Test Groups II and III (Ref. 2).

TABLE 3. DYNAMIC SHEAR TEST LOAD PARAMETERS

Element	Group	Charge density, lb/in^3	Average peak overpressure, lb/in^2	Rise time, ms
DS1	1	1.37	4000	0.05
DS2	1	1.83	4700	0.05
DS3	1	0.91	3300	0.07
DS4	1	1.37	3500	0.05
DS5	1	1.83	5000	0.10
DS2-1	2	2.29	6000	0.05
DS2-2	2	1.83	6000	0.10
DS2-3	2	1.14	3200	0.05
DS2-4	3	2.29	6000	0.05
DS2-5	3	1.60	5500	0.10
DS2-6	3	1.14	4000	0.05

AVAILABLE EXPERIMENTAL DATA

Information deemed important for structural response analysis prior to the testing of the structures included the following quantities: airblast pressure, interface pressures, active and passive strains in the longitudinal reinforcement, soil stress, accelerations (tests DS3, DS4, and DS5 only), and slab deflections. In order to acquire these data, the tests were instrumented as shown in Figure 5.

The blast pressure gages measured the actual pressure generated by the foam HEST charge, whereas the interface pressure gages measured the pressure transferred from the soil layer above the roof to the roof slab (i.e., the actual load the slab "feels"). Active strain gages on the steel were used in all tests to measure compressive and tensile stresses in the roof slab, whereas a passive measure of ductility was obtained by scoring the rebar at specific intervals along the length prior to load application. Finally, deflection profiles of the underside of the roof slab element were obtained through the use of high-speed photography.

A complete summary of the digitized data recovered from the eleven tests can be found in (Ref. 2). In general, the recovered data for airblast pressure, interface pressures, accelerations, and deflections were good. Unfortunately, some of the data were "clipped" at very early time because of extreme pressures, were subject to recording noise due to very high frequencies, or were improperly digitized because of calibration errors. Due to these circumstances, some of the data (active strain for example) were found to have only limited use or increased uncertainty.

Despite these limitations, however, much of the data were discovered to contain very useful information pertaining to the structural response of the reinforced concrete box. In the next section, the experimental information used for this study will be discussed. The subjective counterpart to experimental information in the form of expert opinion will also be described in Section III.

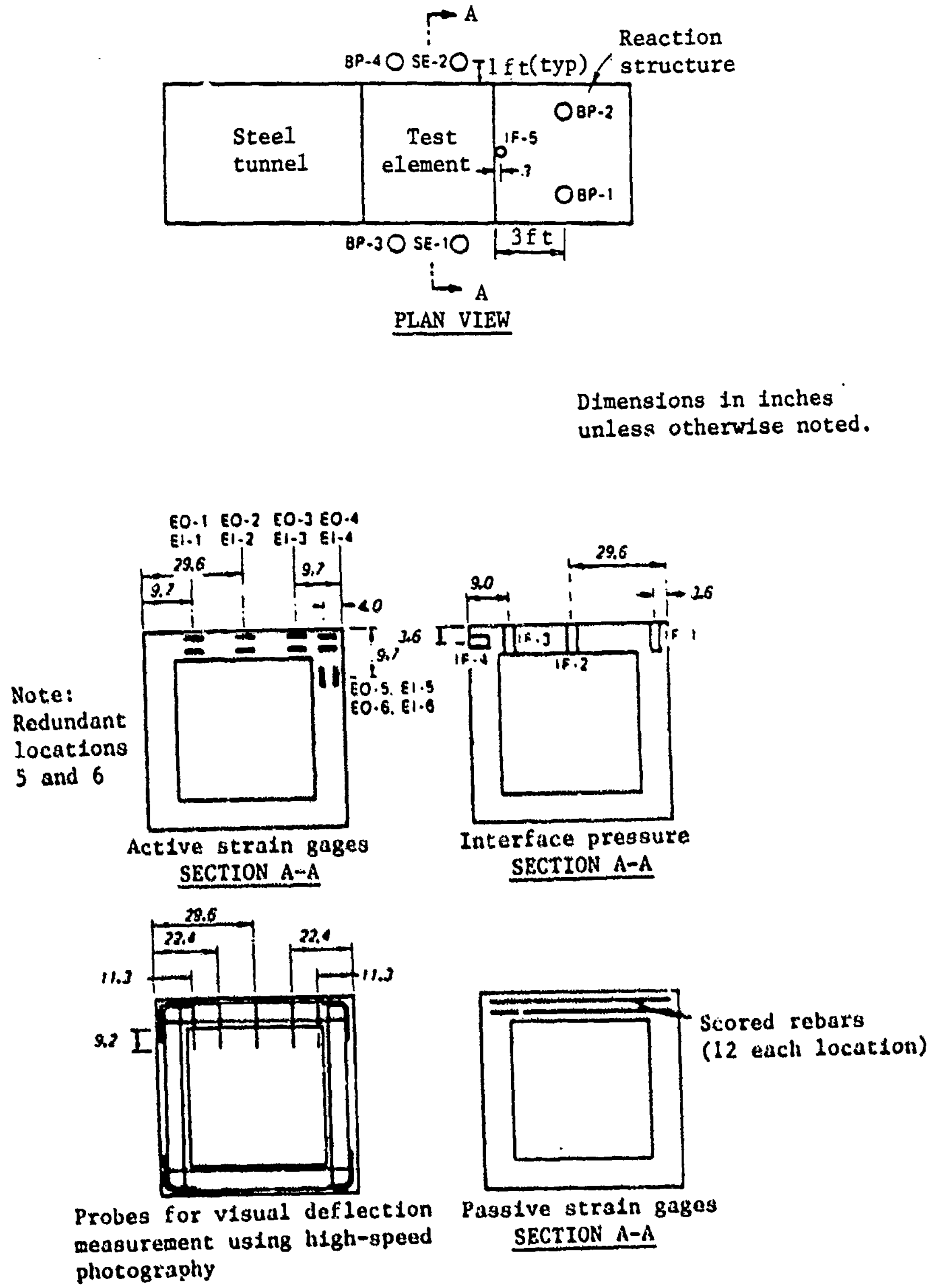


Figure 5. Test instrumentation layout, Test Groups II and III (Ref. 2).

III. ANALYSIS OF SUBJECTIVE AND OBJECTIVE INFORMATION

OVERVIEW OF DAMAGE TO CONCRETE BOXES

In order to have a complete understanding of the buried protective structure problem, a description of the damage sustained by the test elements is presented. Following this, a brief outline of parameters affecting the dynamic behavior of the structure's response is given. By first previewing this information, it is possible to proceed to the more important topics of subjective data and objective data used to qualify and quantify modes and levels of damage.

Photographs of the eleven tests are shown in Appendix A. Since the original purpose of the tests was to study direct shear failure under very high overpressures, it was only natural that the majority (7 of 11) of the tests were subjected to complete collapse of their respective roof element, whereas only four concrete test boxes were loaded to noncollapse levels. Although four of the eleven test elements did not completely collapse, it has been reasoned that all boxes failed initially in a shear or shear-flexure mode (Ref. 4). However, upon inspection of the posttest photographs, the variation in post-failure damage is found to be fairly large.

As was predicted prior to the tests, several of the specimens failed in a direct shear mode. Inspection of element DS5, for example, reveals that the roof slab was completely severed from the walls of the structure along nearly vertical failure planes. Approximately 60% of the principal reinforcement was broken along these two faces, together with slight necking down of the reinforcing bars. The remainder of the reinforcing bars were pulled out of the roof supporting wall during failure. Inward translations of the tops of the walls were 3 to 4 in from the vertical. Considerable cracking was noted along the base of the structure, as well as at the intersection of the wall and the base slab. Most of the concrete in the roof slab which fell was found to be crushed and easily crumbled except in the middle third of the slab.

In a slightly different scenario, inspection of test element DS2-1 indicates that all reinforcing bars along the west wall (see Figure A-7 in Appendix A) were completely severed along a near vertical surface, as in DS5 above. Unlike DS5 though, the east failure plane was not this same type.

Failure obviously occurred along the west wall first, followed by rotation and reinforcement pullout along the east wall until collapse. This asymmetric failure could have been caused by a nonsymmetrical load, and/or poor workmanship during construction.

Test elements DS3 and DS2-5 represent cases in which the structure sustained severe to very extensive damage but had enough residual strength to resist complete collapse. Permanent deflections of 10 and 12 in for test elements DS3 and DS2-5, respectively, were recorded. In both cases, large vertical offset (abrupt edge displacement) and sharp rotation of reinforcing steel at the slab/wall interface, indicate an initial shearing action. While the more heavily loaded DS2-5 is curved throughout its span, the middle third of test element DS3 remained relatively flat. Note also the large inward translations of the tops of the walls in element DS2-5. The concrete cover was broken up over the entire span, and virtually all the concrete cover on the underside of slab DS2-5 spalled off, exposing the principal reinforcing steel. Similar damage can be seen in the DS3 element but not nearly to the same degree. Perusal of the load parameters in Table 3 shows that the roof element of test DS3 was loaded to approximately 2000 lb/in^2 less than the DS2-5 element. Thus, by inspection, it can be seen that these two tests responded similarly; but the late-time impulse in the first case was not enough to force it to the same level of damage as in the second case.

Observations of test elements DS2-6 and DS2-3 show instances where the level of damage attained was only slight to moderate when compared to the tests discussed previously. Permanent deflection is 3 to 4 in for each specimen. Note again, the response of both of the structures appears to be predominantly shear, as can be seen by the vertical offset of the roof slab at the slab/wall interface. The slabs remained relatively flat with some cracking on the underside of their central portions. Most of the cracking and crushing of the concrete appears in the region within a distance equal to the slab thickness from the wall.

PARAMETERS AFFECTING DYNAMIC RESPONSE

The response of slabs under dynamically applied loads is a function of the load magnitude and distribution, slab characteristics, and boundary conditions. Thus, because of the complicated interaction of variables

involved in slab behavior under simulated blast overpressures, there is no simple way to predict modes of structural response. Therefore, before proceeding with an investigation of soft and hard data that are available for describing modes of response, a brief overview of parameters affecting structural behavior is warranted.

In studying the response of these structures, it is important to have an idea of whether shear or flexure typically controls response, and how and when shear and flexure each attain their failure levels. The term failure is defined here as the point at which the concrete element reaches its ultimate capacity (either in shear or in flexure). It is also important to note at this time that failure in a given mode does not imply collapse of the structure.

It is known that, under rapid rates of loading and strain, the apparent material strengths of both steel and concrete are significantly increased, as shown in Figure 6. Because of this, the determination of the dynamic ultimate

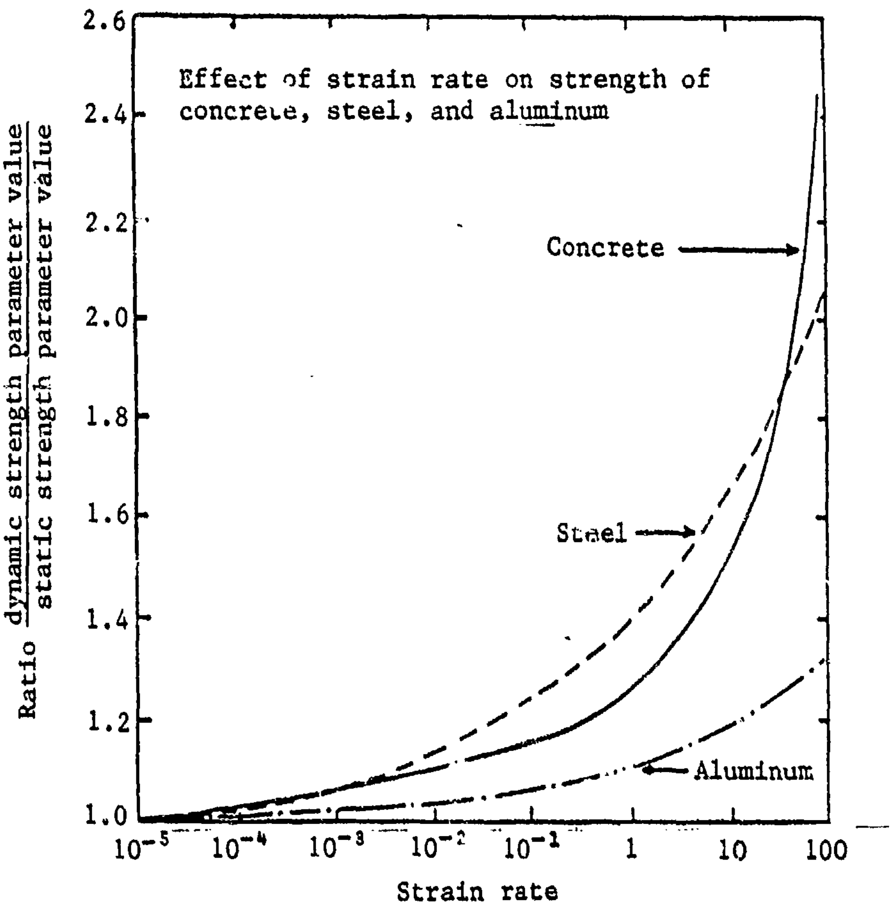


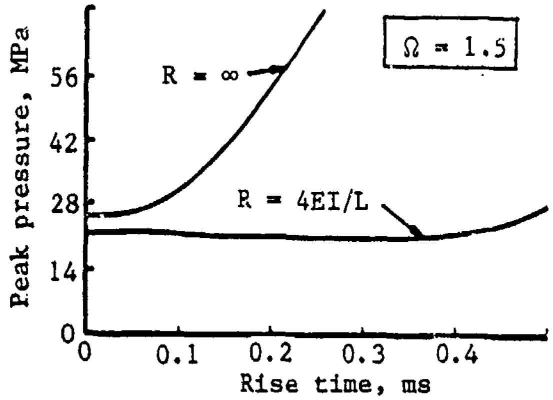
Figure 6. Dynamic strain rate effects on strength of concrete, steel, and aluminum (Ref. 5).

capacity of a member is a difficult task. Therefore, in the case of an impulsive blast load, it is especially important to understand the effects induced by changes in strain rate in order to predict, design, and protect against failure.

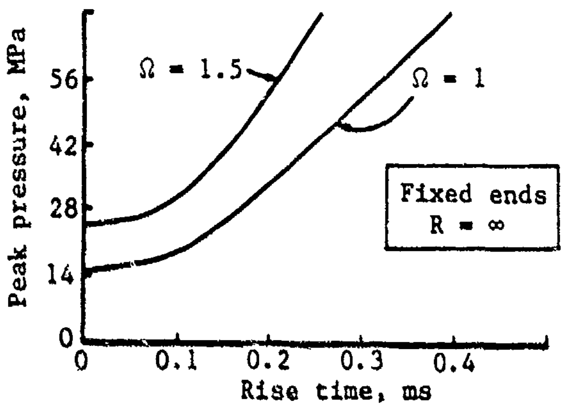
Ross (Ref. 4) used a viscoelastic Timoshenko beam to study the effects of load rate on incipient elastic failure at slab supports (assuming that one-way slab response is similar to that of a beam). More specifically, he studied the combination of conditions which were necessary to produce either direct shear or flexure failure and their relative likelihood of occurrence. His findings included the fact that shear force tends to be amplified more than bending moment in early time (less than 1 ms) because of strain rate effects. His findings indicate that time to failure in shear is significantly decreased when strain rate effects are included, thus predicting shear dominance over flexure in early time.

Ross also studied the early-time response effects of load parameters, beam end restraint, and length-to-depth ratios under the same types of impulsive load conditions. Excepting load duration, all parameters were found to have some effect on the response of the structure. Direct shear failures precede flexural failures at early time for certain combinations of parameters. Failure curves were produced which related two of the most significant load parameters, peak pressure and rise time, to beam parameters. Typical curves are shown in Figure 7 for slabs with parameters in group 3 (as given in Tables 1 and 2). Note that points falling above the failure curves correspond to direct shear failures and points below tho curve correspond to flexure failures. By comparison with the actual range of conditions experienced in the test series, it was observed that peak pressure and rise time have the largest effects on failure mode.

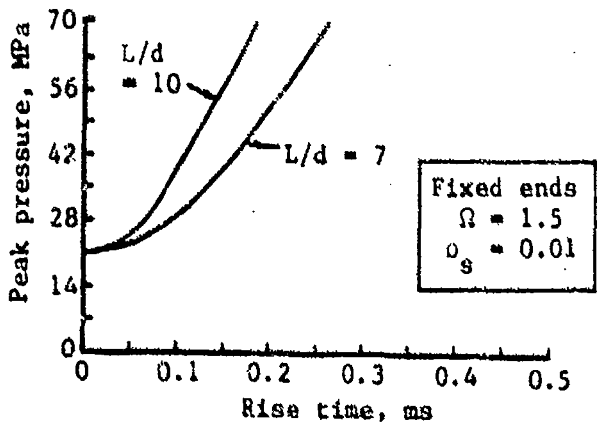
Another dynamic phenomenon related to the buried boxes is pointed out at this time. Actual testing of the reinforced concrete buried boxes showed that previous analytical methods had severely underpredicted the actual strength of these structures. After studying the pressure gages located at the soil/roof interface, it was discovered that significant late time (greater than 1 ms) transferral of pressure from the flexible central portion of the roof to the more rigid supports was taking place. This is due to a phenomenon known as soil arching. Basically, soil arching is the ability of a soil to transfer loads through a system of shear stresses from one location to another in



(a) Influence of end restraint on failure curves (1 MPa = 145 lb/in^2).



(b) Influence of strength enhancement factor, Ω, on failure curves (1 MPa = 145 lb/in^2).



(c) Influence of L/d on failure curves (1 MPa = 145 lb/in^2).

Figure 7. Typical failure curves with Group 3-type properties and fixed ends (Ref. 5).

response to a relative displacement between the locations. Although the effects of soil arching are usually neglected when the depth of burial is less than the clear span of the roof, its effects on late-time interface pressure distribution over the slab length can be rather significant. Although the arching phenomenon does not influence early time incipient failure conditions, it can be a significant feature to consider in late time, if there is a sufficient interface impulse to cause collapse.

SUBJECTIVE INFORMATION

Obtaining Expert Opinion

As mentioned in Section I, the assessment of damage to a structure may be a combination of both subjective and objective information, as seen in Figure 8. In this report, the term subjective information is meant to describe information that resides in the minds of experts in a particular field who have, over time, accumulated in-depth knowledge in their subject-field. Judgment of this type is used often in engineering evaluations, especially to compensate for sparse data and for extrapolation outside a given data range.

For this study, the engineering judgment was obtained by polling experts in the area of structural damage. A questionnaire concerning the damage to the roof element of the 11 test structures described previously was mailed to 60 structural engineers across the United States (35 responded). The questionnaire contained posttest photographs (see Appendix A) of all the test elements.

The purposes of the questionnaire were threefold. First, it was hoped that information obtained from the questionnaire could be used to help determine how experts arrive at their evaluations of conceptually difficult problems. The second purpose was to determine how or why their answers were the same or different. The third purpose was to determine if it is possible to aggregate these assessments into a single data base.

The format of the questionnaire was quite simple. For each picture, the expert was asked two questions dealing with the damage shown in the given picture. First, "What is (are) the mode(s) of response of the roof element?"; and second, "What is the degree of damage to the roof in that mode?" Along with their responses to the two questions, the experts were asked to provide

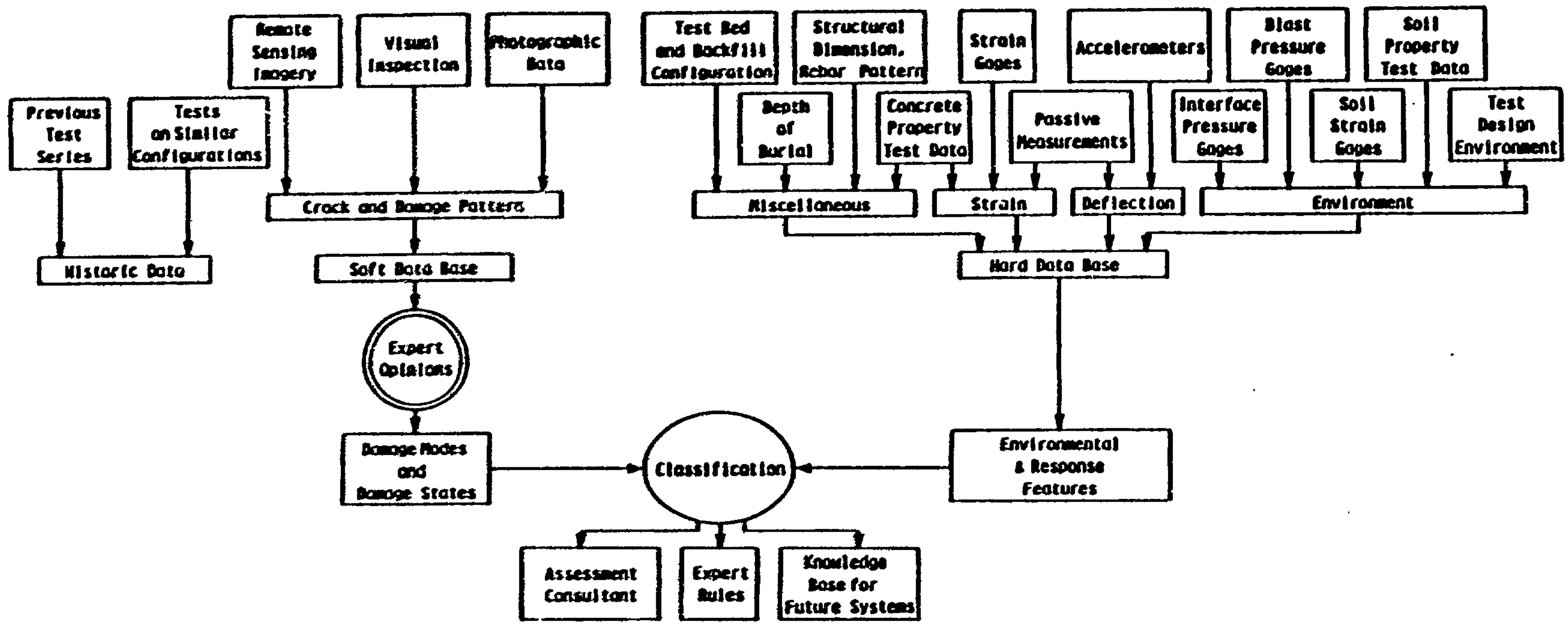


Figure 8. Possible sources of soft and hard data for use in damage assessment analysis (Ref. 6).

their reasonings to substantiate their answers. The first question was designed to be qualitative in that linguistic responses were expected. Acceptable answers might include "direct shear," or "flexure followed by tension membrane," etc. The second question was intended to be more quantitative in content (example: slight damage = 1/10, or total damage = 10/10), although linguistic answers with appropriate explanations were also acceptable.

The questions asked of these experts were relatively vague in content and were designed as such in order to avoid any built-in bias on the part of the author. Uncertain wording of the questions allows the expert to interpret the meaning without external constraints forcing his judgment and allows the most information to be derived from a single question. On the other hand, inherent vagueness within a question also increases the possibility of confusion and noncomprehension.

Analysis of Expert Opinion

One of the main problems encountered with the analysis of the questionnaire was the difference of opinions expressed in their reasoning by the experts. Varying backgrounds among the experts is one possible explanation, because some of them were familiar with the experimental test series and some were not. Thus, some of those interviewed had unfair insight into the questions asked. A second problem encountered when analyzing the responses was the interpretations of ambiguous technical and linguistic terms, such as "severely damaged," or "deformation near wall is small." Another problem was associated with a lack of information. Some of the experts were hesitant or confused in their responses simply because specific information on structural parameters, functionality issues, or repairability problems were not provided to them.

Besides the large amount of raw data obtained, other positive aspects were ascertained from the questionnaire. First of all, it was discovered that, in general, experts were comfortable in giving their opinions even though the pictures submitted to them were poor quality and the information was incomplete. Secondly, many of the experts were able to predict the actual chronology of events leading to deformation and/or failure using only visual data.

Having considered the initial impressions of the experts' responses, the most important questions that might be asked next are, "What do we do with all this raw information?", and "How do we decompose it into knowledge that can be implemented into a computer code?" As pointed out above, the greatest difficulty arises when we examine the data and discover the variety of linguistic terms put forward by the experts and the wide variety of images or situations these terms describe. Initially, some confusion arises in trying to decide whether different terms represent different explanations, or if they are using different terminology to describe the same concept. For instance, some of the terms used to describe a shearing action include: shear, punching shear, pure shear, direct shear, vertical shear, edge shear, and sliding shear.

After careful analysis of the data, however, it became obvious that these problems are somewhat superficial and that there was a tendency (whether conscious or unconscious) on the part of the experts to break their reasoning up into smaller components of the problem. For instance, on the topic of damage level, the experts tended to place their reasonings into one of three categories; structural integrity, functionality or use of the structure, and repairability of the structure. Typical responses given for "slight," "moderate," and "severe" damage levels appear in Tables 4 through 6. As can be seen from the tables, most experts grouped their reasoning into the category of structural integrity. This is understandable, as they were given no information other than the photographs and thus relied heavily on the structural portion of their intuitive knowledge.

On the subject of modes of failure, further investigation revealed that, within the category of structural integrity, the experts tended to specify their reasonings depending on the mode of response they believed was involved. Virtually all descriptions were closely related to one of the four major mode groups: shear, diagonal tension, flexure, or tension membrane.

From this point, it was observed that the data could be further subdivided into specific structural attributes or parameters dealing with three unique locations along the span of the roof, i.e., the middle portion of the slab, the slab near the walls, and the wall supports. Tables 7 and 8 show some of these attributes along with typical descriptions volunteered by the experts for shear and flexural modes. Similar tables for diagonal tension and tension membrane can also be created.

TABLE 4. EXPERT REASONING GIVEN FOR SLIGHT DAMAGE

STRUCTURAL INTEGRITY

- minimal permanent deflection
- damage localized at supports
- no rebar problems and minimal dispacement
- small support rotations
- still in good shape
- minimal tensile cracking at centerline and support
- considerable capacity remains
- no plastic hinge formation
- small crack lines
- most structural resistance remains

FUNCTIONALITY

- still usable
- system remains functional
- everything inside should have survived
- can still be used for the purpose for which it was designed
- reusable

REPAIRABILITY

- small permanent deflection can be repaired

TABLE 5. EXPERT REASONING GIVEN FOR MODERATE DAMAGE

STRUCTURAL INTEGRITY

- end roof still in place even though significant spalling has occurred
- plastic hinge not fully developed
- onset of membrane action
- rebar cage still intact
- lots of cracking and permanent set
- some tensile pullout and shear punch on right side

FUNCTIONALITY

- some unobstructed clear space is provided
- slight rotation of walls
- contents probably OK
- most equipment would survive
- small debris would fall on contents
- structure may still be useful for something

REPAIRABILITY

- structure serviceable
- minimum repair needed
- probably repairable

TABLE 6. EXPERT REASONING GIVEN FOR SEVERE DAMAGE

<u>STRUCTURAL INTEGRITY</u>

- very large permanent deformation
- severe spalling at joints
- most of concrete has spalled off roof
- yielded reinforcing, spalled concrete
- on verge of collapse
- large support rotations
- no longer able to withstand blast pressures
- shear hinge at support is fully developed
- end supports nearly broken

<u>FUNCTIONALITY</u>

- only short-term use is possible
- reasonable chance for survival
- spalling would have harmed contents
- contents severely shaken
- significant debris and pressure ingress
- associated shock and vibration would have severely damaged contents

<u>REPAIRABILITY</u>

- needs a lot of work
- roof needs replacing
- could possibly be repaired for temporary use

TABLE 7. EXPERT REASONING GIVEN FOR SHEAR DAMAGE

Location	Attribute or Parameter	Expert Description
Main slab (middle 1/3 to 1/2 span)	Curvature	- relatively flat - rebar cage appears to be flat - almost uniform displacement
	Crack Pattern	- not many cracks visible - no yield lines @ centerline - no crushing in the compression zone @ top centerline
Slab Near Wall	Displacement	- clean vertical break - local vertical deformation - mostly at supports - relative displacement at edges - sharp gradient
	Anchorage	- sharp bending of bars at support - broken bars - apparently yielded reinforcement - rebar severed at wall - rebar violently ripped out
	Crack Pattern	- diagonal cracking - can see diagonal struts
	Spalling/ Crushing	- considerable concrete crushing
Walls	Rotation	- minimal inward rotation
	Spalling/ Crushing	- wall supports remain intact with little concrete crushing

TABLE 8. EXPERT REASONING GIVEN FOR FLEXURAL DAMAGE

Location	Attribute or Parameter	Expert Description
Main slab (middle 1/3 to 1/2 span)	Curvature	- smooth top bar curvature - moderately curved roof - interior flexural hinge formation
	Crack Pattern	- cracks indicate 3-hinge mechanism - most cracks are on the bottom at the centerline - crack and deformation pattern
	Spalling/ Crushing	- crushed concrete at top centerline - spalling at centerline
	Displacement	- large displacement at centerline
Slab Near Wall	Curvature	- large rotation near wall
	Anchorage	- bars pulled out without evidence of yielding
	Displacement	- lack of vertical offset at wall
	Crack Pattern	- cracks indicate flexural hinge formation - tensile cracks at top edge - crack lines at top face
Walls	Rotation	- minimal inward rotation of walls
	Spalling/ Crushing	- concrete crushed in compression zone of wall face

Interestingly, if we take a close look at the attributes described previously, we notice they are very similar to those used to describe the levels of damage. For instance, "large deflection at wall" could be used to describe a shear mode, but it could also be used as an indication of severe damage. Thus, by reducing or subdividing the expert information into lower levels of knowledge as seen in Figure 9, attributes or parameters can be defined that describe both modes of failure and levels of damage.

Note too that, by carefully choosing the wording for these attributes, the meaning can be varied by changing only the adjective used to describe it. In the example given, for instance, the attribute is "deflection at the wall." By simply changing the associated adjective from "large" to "none (no)," we change the meaning and are thus able to use the same attribute over a wide range of conditions. However, an obvious problem arises because the meaning of such terms as "large," "slight," "none," etc., must now be defined.

Once we have solved this problem of terminology, we have a unique set of linguistic attributes that we can use to describe modes of response and levels of damage. In all, ten of these structural attributes or parameters were identified within the experts' responses. These ten attributes are listed in Table 9. The use of these attributes in the knowledge combination process is illustrated in Section IV. More specifically, expert opinion relating modes of damage to the attributes will be combined with (user supplied) observations of attribute levels to produce output identifying modes and levels of damage.

OBJECTIVE INFORMATION

As stated in the introduction, one of the goals of this study was to be able to combine objective data with the subjective information outlined above. Before this can be done, it must be determined which data are the most useful, and what is the most efficient manner in which to implement the data into the knowledge base. Previously, when we referred to objective information, it was stated that we were talking about "hard" data such as digitized waveforms, etc. Although these data are crisp in the sense that the data are quantifiable, this information is not without inherent subjectiveness when it is applied to the difficult task of interpreting modes of failure.

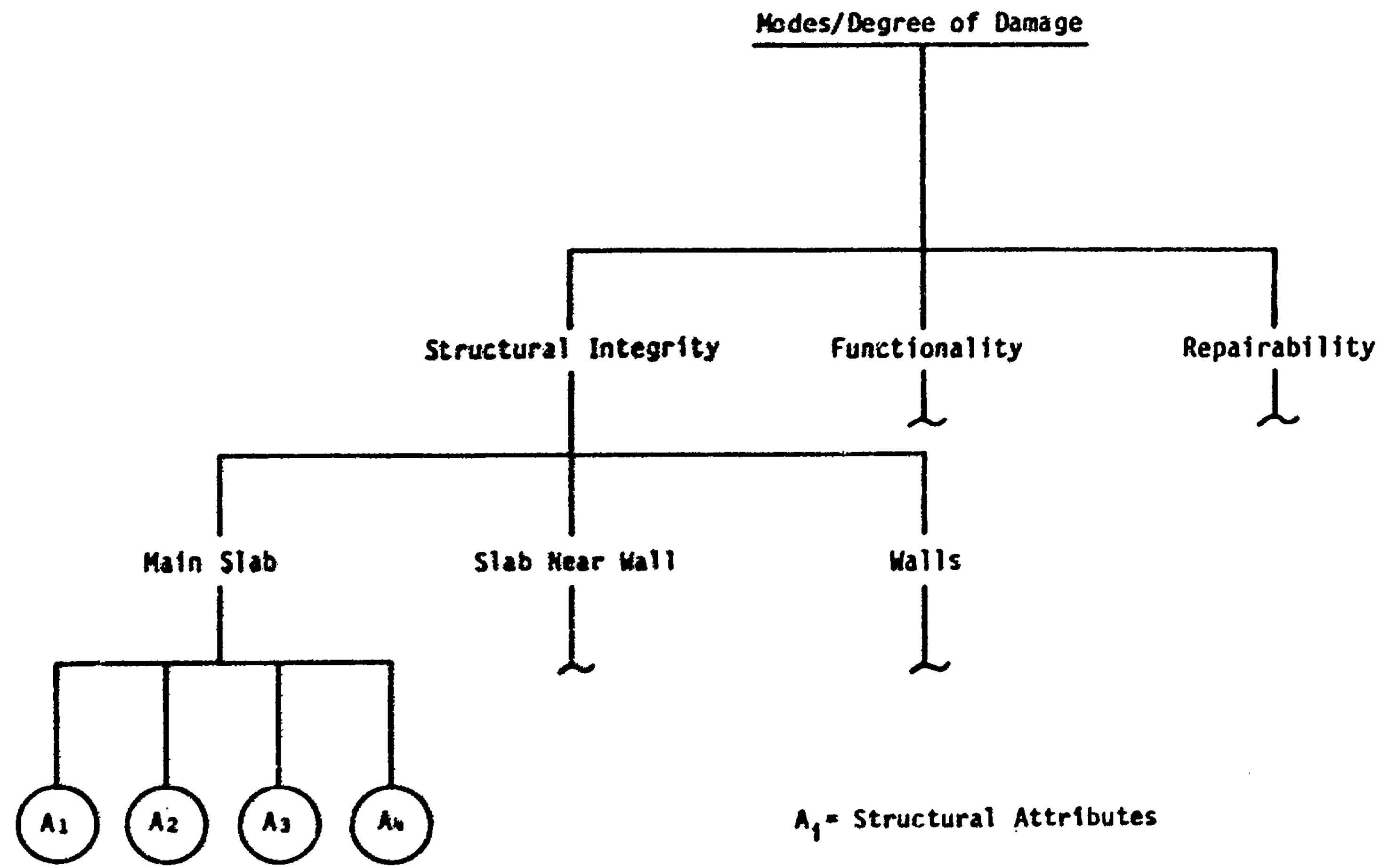


Figure 9. Reducing expert opinion to lower levels of knowledge.

TABLE 9. STRUCTURAL ATTRIBUTES DEVELOPED FROM EXPERT RESPONSES

Attribute	Description
1	Spalling and loss of concrete/rebar interaction on the bottom side of the main slab (central 1/3 to 1/2 span)
2	Crushing of concrete on the top side of the main slab (central 1/3 to 1/2 span)
3	Vertical offset (step function shape with slab top displacement relative to edge support) in the slab/wall connection region
4	Rotation of the roof slab in the slab/wall connection region
5	Curvature of the main slab (central 1/3 to 1/2 span) with corresponding differential deflection (centerline minus near wall) to slab length ratio
6	Flexural related cracking (including yielding, hinge formation,... of the centerline main slab and tensile cracks at the top side of slab/wall connection
7	Inclined cracking at roughly t/2 from the wall face (at approx. 45 degrees to the horizontal)
8	Spalling and loss of concrete/rebar interaction in the slab/wall connection region
9	Inward rotation of the tops of the walls
10	Crushing of concrete and loss of concrete cover or rebar anchorage in the wall supports themselves, or in the slab/wall joint

Damage Modes

The amount of information that can be obtained from digitized waveforms is enormous. From interface pressure data alone, the number of features that can be derived to aid the mode identification process is almost endless. Features such as rise time and peak pressure, frequency in terms of the power spectral density, ratios of various impulse values, and decay slope of the pressure record after peak pressure are but a few of the possibilities to be investigated. Whether or not each feature contains information regarding modes of failure is a separate question.

For this study, experimental test equipment provided numerical data for analysis of roof slab response modes in the form of digitized interface pressure waveforms, deflection profiles from high-speed photography, passive and active steel strains, and velocity/acceleration versus time records. The significance of each of these objective parameters is discussed next.

For each of the eleven tests, interface pressures were available at three locations along the roof span as was shown in Figure 5. Ross and Krawinkler (Ref. 7) pointed out that the pressure decay after initial peak was a good indicator of early time response (less than 1 ms) of the roof slab. They noted that pair-wise comparison of the three pressure records would indicate whether shear or flexure response dominates at early time.

In the event of a flexure controlling failure, pressure plots are similar for locations 1 and 3 and different than location 2, as shown in Figure 10. Rapid decay of the relatively flexible centerline of the slab indicates movement downward, while readings near the support and over the wall remain higher for a longer period of time. These sustained high pressures indicate a rigid boundary condition with these two locations (1 and 3) "seeing" little downward movement.

In the event of a shear controlling failure, pressure plots at locations 2 and 3 become similar in shape and decay much more rapidly than those at location 1, as shown in Figure 11. Here again, the pressure at location 1 stays higher, longer, indicating a rigid boundary condition. Rapid decay of pressure at location 2 and location 3 indicates downward movement of the entire slab as a rigid body. The only way for this to happen would be for an initial slip to occur at the support.

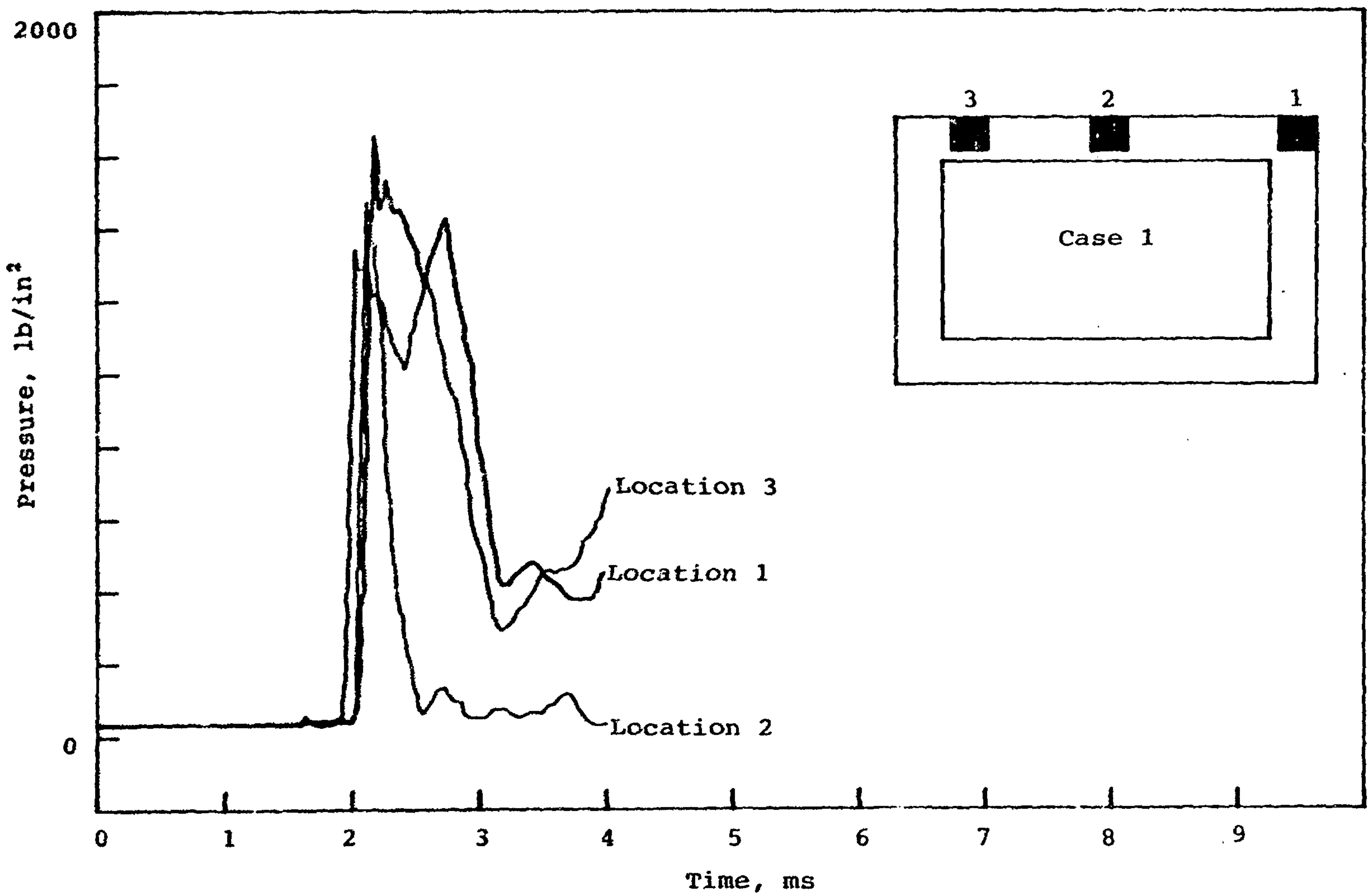


Figure 10. Interface pressure plot of typical flexural failure response.

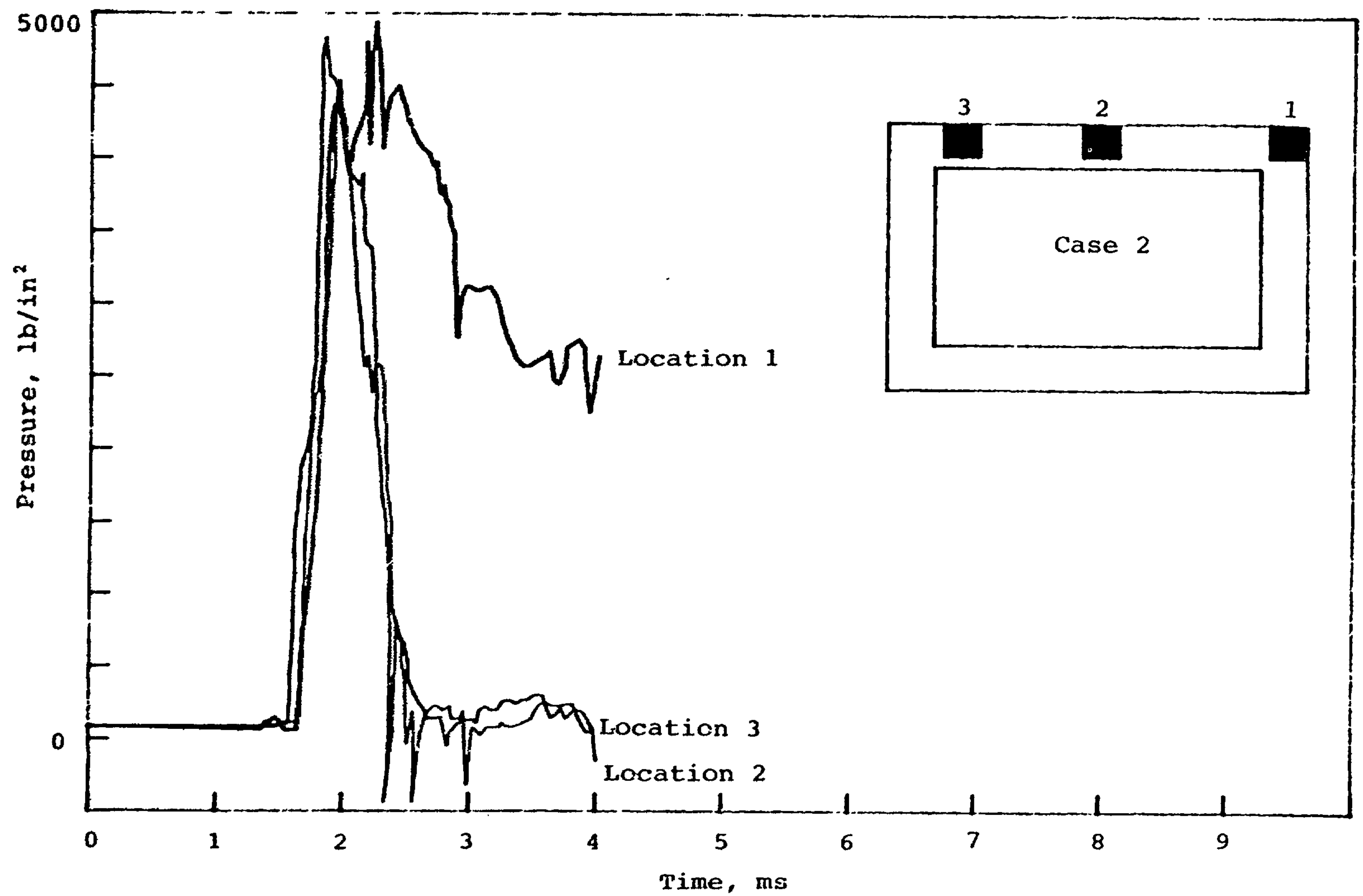


Figure 11. Interface pressure plot of typical shear failure response.

As mentioned previously, this information is not purely "objective." The graphs in Figures 10 and 11 are for two tests conducted prior to the 11 dynamic shear tests (see Ref. 3). The flexure and shear conditions are evident in these two cases. But in the event that the similarity of the pressure at specified locations is not this clear-cut, how does one go about deciding just how "similar" the graphs are at each location?

Active steel strains (shearing and normal) are useful in providing information regarding whether a shearing action or flexural action has occurred. As pointed out in Section II, however, because of high recording noise, strain measurements at early time were indiscernible. However, late time response of the slab element in the form of flexure or membrane action can be predicted. In the case of a fixed-fixed beam, flexure is denoted by tension in the top reinforcement and compression in the bottom reinforcement at the support, with the reverse being true at the centerline. A complete membrane response is indicated by tension in all reinforcement. If initial shear controls because of dowel action at the support, it is possible for both top and bottom reinforcement to be in tension, while the central portion of the slab responds as a flexural element with compression in the top and tension in the bottom. Passive strains obtained from scored rebar have little use except for measuring overall ductility associated with total collapse.

In general, velocity/acceleration graphs can provide insight to trends in the response when combined with shear strain data. For instance, modes of damage are recognized in the data by certain features in the midspan velocity-time histories. A dip in the velocity following the initial peak indicates flexure is dominant, while a monotonic increase to peak velocity indicates shear is dominant. The reason for these trends is based upon rigid body motion concepts similar to those discussed previously for the interface pressures. Because of the fact that only three of the eleven test elements (DS3-DS5) were equipped with acceleration gages, more velocity/acceleration data are needed for analysis before mode predictions can be made with any confidence.

Typical deflection profiles obtained from high-speed photography for tests DS3 and DS2-5 appear in Figures 12 and 13, respectively. Rotation at the support, curvature of the central portion of the span, and differential deflection ratios from various sections along the roof span can provide measures of mode response. Large vertical offset and sharp rebar rotation at

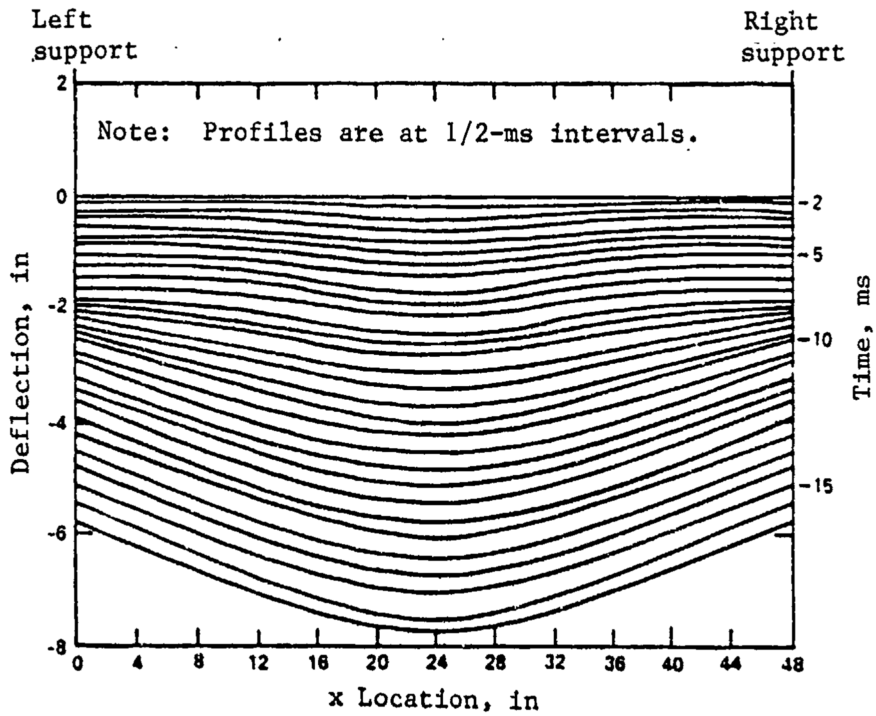


Figure 12. Deflection profiles of Test DS3 (Ref. 2).

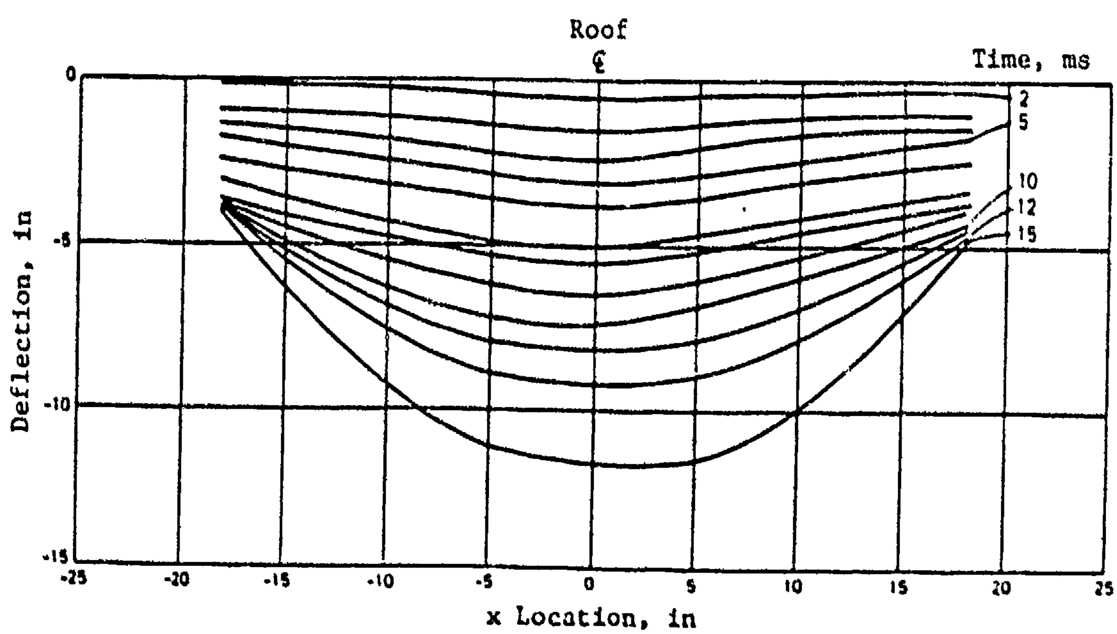


Figure 13. Deflection profiles of Test DS2-5 (Ref. 2).

the wall support, combined with little or no curvature (i.e., flat) of the main slab, indicates an obvious shear response. If sufficient residual strength is available after initial shear, the slab responds in a flexural mode similar to that of a simple beam. And finally, continued loading may force the entire slab into a membrane response where all fibers are in tension and a large curvature prevails at the centerline. To varying degrees, each of these responses can be seen in Figures 12 and 13.

Experimental data from the eleven tests provide a wealth of information for determining structural modes of response. Obviously, not all data are of equal value, nor is it within the scope of this project to examine and incorporate all this information into the computer code. Rather, the objective is to demonstrate the possibilities that are available for analyzing, combining, and incorporating different types of data into a rule-based damage assessment system. Therefore, from the information outlined above, only the interface pressure data and deflection profile information will be used in the code.

The reasons for choosing these two features, interface pressures in particular, were summarized well in Reference 8. First, these two features were the most complete sets of data from the eleven tests. Secondly, they are assumed to have recorded phenomena significantly above the noise levels of the gages. Thirdly, these two features were used in previous analytical efforts in attempts to characterize failure conditions. Finally, these features are an actual measure of the overall behavior of the beam. The methodology used for implementation of these data into the code is detailed in Section IV.

Damage Levels

A significant effort has been expended over the last several years to analyze and understand the structural modes of response controlling the behavior of reinforced concrete boxes to impulsive blast loads (Refs. 3,5,8,9,10,11,12,13,14). Although modes of response are important factors in this study, the damage level imparted to the structure because of these various modes is also of interest. In the section on subjective information it was found that careful decomposition of expert opinion resulted in linguistic attributes that could be used to describe both modes of failure and damage levels. Thus, in this section, we seek parameters obtained from

experimental data that will provide a measure of damage imparted to the structure.

Because of the nature of the loading conditions, the structures in this study can be expected to sustain damage within a broad range (possibly even total collapse) as seen in the photographs of Appendix A. In typical civil engineering structures, it is generally accepted that failure occurs in a member when yielding is first initiated. On the other hand, a protective structure that is subjected to a load which just initiates a yield condition in the roof slab might be considered only slightly damaged if none of the contents has been adversely affected.

From the above discussion we can conclude that the measure of damage in conventional civil engineering structures is much different than in the buried protective structure scenario. We may also conclude that the criterion used in the measurement of damage to typical structures is inadequate for our purposes. Measures of damage used in the past for large inelastic deformations include such quantities as the ductility ratio, rotation ratio, or curvature ratio. Damage measures such as these simply compare the maximum value of a parameter (deflection, rotation, or curvature) to the first yield value. For simple models and static loading conditions, these quantities provide adequate damage measures. However, experimental comparisons of these damage measures in structures subjected to severe load conditions show they are not sufficient to produce accurate damage assessment.

Under earthquake loading conditions, for example, reinforced concrete structures are damaged by a combination of repeated stress reversals (cyclic loading) and high stress excursions. For this reason, the definition of damage in terms of the ductility ratio may be inadequate. As damage accumulates in a structural system, its strength diminishes, and energy is dissipated. Energy dissipation then, as Banon (Ref. 15), Park (Ref. 14), and Wang (Ref. 16) show, can be an effective quantity by which damage is measured. Calculation of the dissipated energy produced by earthquake loads is a relatively straightforward procedure. Single-degree-of-freedom (SDOF) models can be used to calculate the incremental energy dissipated from hysteretic force-displacement diagrams. In the problem under consideration, however, the loading is impulsive rather than cyclic, and the force-displacement relationship is much more complicated. Thus, application and implementation

of similar methods to the buried structure problem would be a formidable task in itself.

Rather than spend unnecessary amounts of time developing complicated damage models, the authors found it more advantageous to investigate the available experimental data for features to use as possible damage measures. Data chosen for investigation included the interface pressure data and the deflection data for the same reasons outlined under Damage Modes. Influenced by the discussion above on energy, initial attempts by the authors to find a damage level indicator were concentrated on the interface pressure data. Calculations of the energy per unit area as given by Equation 1 and impulse per unit area as given by Equation 2 were performed for each test.

$$\text{Energy} = \int_{\delta_1}^{\delta_2} P \cdot d\delta \qquad (1)$$

$$\text{Impulse} = \int_{t_0}^{t_1} P \cdot dt \qquad (2)$$

In these equations, P is the interface pressure at a specific point along the roof slab, δ_1 is the deflection of the roof slab at a specific point at time t_1 , and δ_2 is the deflection of the roof slab at the same point at time t_2

Various summations and ratios of these values were tabulated and compared to each other for usefulness as damage measures. Little correlation was found between some of the calculated values and actual damage levels of the tests. This is due in part to the fact that pressure data are available for only three points along the length of the slab, thus making it difficult to obtain a true measure of the entire roof response.

Although some of the features which were calculated exhibited fair within-group trends of damage (i.e., compared well with linguistic damage level assessments), none of the features studied could be used to show trends of damage for all groupings. In other words, none of the features was adequate in classifying damage for all 11 tests.

Deflection profiles were examined next because of the inherent information contained concerning damage/deformation. The calculation for one of these damage features is shown in Table 10. Note that the magnitudes of the normalized values compare well (within the group) relative to the

TABLE 10. CALCULATION OF VALUES FOR A TYPICAL DAMAGE LEVEL INDICATOR

$$\text{Damage Indicator (D.I.)} = \int_0^{10} \delta_{C} \cdot dt + \int_0^{10} \delta_{wall} \cdot dt$$

where $\delta_{\mathfrak{C}}$ is the centerline roof slab deflection at time t, and δ_{wall} is the deflection of the roof slab near the wall at time t.

Test No.	Group	Visual damage assessment	D.I., in-ms	Normalized D.I.
FH1[a]	1	Slight	18.41	0.22
FH2[a]	1	Total (collapse)	81.94	1.00
DS1	1	Total (collapse)	NA[b]	
DS2	1	Total (collapse)	74.69	0.91
DS3	1	Severe	27.49	0.34
DS4	1	Total (collapse)	50.39	0.61
DS5	1	Total (collapse)	79.14	0.97
DS2-1	2	Total (collapse)	62.16	0.76
DS2-2	2	Total (collapse)	74.92	0.91
DS2-3	2	Moderate	32.63	0.40
DS2-4	3	Total (collapse)	68.59	0.84
DS2-5	3	Very Extensive	48.01	0.59
DS2-6	3	Moderate	NA[b]	

[a] Data obtained from Foam HEST Tests (see Ref. 3).
[b] Deflection data not recovered

Note: Values were normalized by dividing by the largest D.I. (Test No. FH2).

linguistic assessment (i.e., total damage corresponds to values approximately equal to 1.0, and slight or moderate damage corresponds to values much less than 1.0). As with the energy and impulse features, few of the deflection features were able to predict damage levels for all 11 tests.

After careful study of all the features calculated, it was concluded that the phenomenon of within-group agreement is caused by variation in the major test parameters (f_c', P, L/d). Although much work has been conducted on the interaction of these parameters with respect to modes of response, it is not known with confidence how these parameters affect late-time deformation response.

Despite all the problems encountered with the data, a rather simple, but effective feature based on deflection profiles was chosen for inclusion into the computer code for demonstration purposes. The damage level value for any given test is computed using Equation 3.

$$\text{Damage Level} = \frac{\int_0^L \delta \cdot dx}{L \cdot t} \tag{3}$$

The time of 15 ms was chosen because most deformation has taken place by this time. The parameters L (slab length) and t (time) are inserted into the denominator to normalize the damage indicator, thus simplifying the damage scale. By comparing values calculated for each test with linguistic assessments, a scale (shown below) was created for classifying damage levels.

```
                                                  Very
  None     Slight   Moderate   Severe     Extensive  Collapse
 |--------|--------|----------|----------|----------|--------->
0.0      0.2      0.4        0.7        1.0        1.3
```

In this section, all the information needed to adequately describe the modes of response and levels of damage present in the buried concrete box structure have been described. The only remaining task, therefore, is to integrate this knowledge into an efficient, user-friendly code. In the following section, the methodology used to accomplish this task is discussed in detail. This discussion includes both the theory behind the techniques and

the computer algorithms used to implement them. And, in order to help the reader understand the program which has been developed, an example session using the DAPS code is presented in Section V.

IV. THE STRUCTURE OF DAPS

Before the actual organization of the DAPS code is discussed, it is necessary to present the underlying theory on which the code is based. The first two subsections of this section review some important concepts concerning expert systems and fuzzy set theory. This review should help the reader understand the basis on which the code is developed.

A RULE-BASED EXPERT SYSTEM APPROACH

Expert systems are an outgrowth of a subdiscipline of Artificial Intelligence (AI) research begun in the mid-1960s. Early researchers in the field of AI were interested in building machines capable of pattern recognition, sensory perception, learning, and comprehending the semantics of human thought. Although the major use of computer technology over the years has been in arithmetic operations, AI focuses on the use of the computer as an idea processor rather than a number cruncher.

Expert systems are but a small fragment of the AI field. The purpose of an expert system is to play the role of a consultant or an expert operating in a very restricted domain of knowledge who gives advice to someone with a task or a problem within that domain. In other words, expert systems try to capture a little of the complex process of human reasoning. In its simplest form, an expert system is a collection of knowledge in the form of "rules-of-thumb," as practiced by the domain expert, together with special techniques for applying the proper rule at the proper time.

A question that might arise at this point is "How does one recognize a good candidate problem for expert system implementation?" A response to this question is shown below as a list of identifiable expert system characteristics.

- A relevant body of knowledge exists and is available
- The skill involved is one which could be taught to a new employee
- The knowledge can be expressed in bite-sized pieces that make sense standing alone
- Solving the problem without a computer takes an expert no less than

a few minutes, and no more than a few hours

- The benefit that will come from developing the system is sufficient to justify the cost involved
- The problem contains subjective parameters which are inherently difficult to quantify

As we see in Figure 14, the two major parts of an expert system include a knowledge base and an inference mechanism. The knowledge base is the storage facility for heuristic rules; it attempts to emulate the complex processes of deductive and inductive human reasoning. The heuristic knowledge in the knowledge base has been collected from one or several human experts and is composed of condition-action statements in the form of IF-THEN type rules.

The inference mechanism is the portion of the code separate from the knowledge base which uses the rules together with data from the user to "reason" through a problem. During each cycle, the conditions of each rule

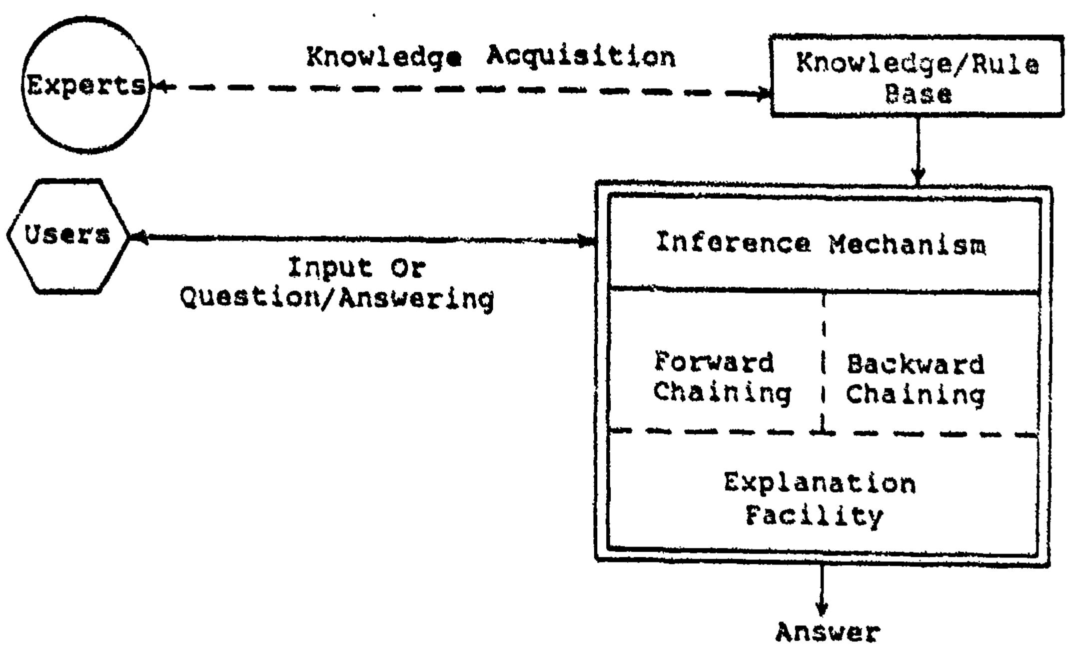


Figure 14. Typical expert system configuration.

are matched against the current state of facts. When conditions stated in the IF portion are matched, actions are executed in the THEN portion. The THEN statements (consequents) then become part of the facts base. These actions affect the current state of facts, making it possible for new rule conditions to be initiated. The inference process in most current expert systems is keyed to a search-and-match strategy of this type. A rule will not be triggered if there is the slightest discrepancy in matching. Also, one rule may activate several other rules, and the propagation of rules may proceed either forward or backward or a combination of both.

This forward or backward propagation of rules describes the two types of inference mechanisms. The first, known as forward chaining, is simply a bottom-up search. Starting with low-level facts, information is deduced until a final conclusion is reached.

Example:	Rule 1	IF:	A
		THEN:	B
	Rule 2	IF:	B
		THEN:	C

Given A is true, then the conclusion C is reached. The second method, known as backward chaining, is a goal-oriented search. Starting with an assumed final conclusion, the system works backward through the rules until it finds sufficient data to establish the conclusion or goal.

Example:	Find out about C		(goal)
	IF: B	THEN: C	(Rule 2)
	IF: A	THEN: B	(Rule 1)
	IF: A	THEN: C	(Implicit Rule)

For this study, various inference mechanisms were investigated for possible use. In particular, the inference mechanism in SPERIL-1 (Ref. 17) was thoroughly examined. The inference mechanism used in SPERIL-1 is a backward chaining mechanism using the Dempster-Shafer theory of evidence to process uncertainties in the knowledge base. After careful analysis it was determined that an expert system shell would be used. An expert system shell is essentially a complete expert system minus the knowledge base. The shell

chosen for this project is called EXSYS and is available for use with personal computers. A brief outline of the features and capabilities available in EXSYS are presented in Appendix B.

UNCERTAINTY AND THE USE OF FUZZY SETS

Fuzzy Set Theory as an Approximate Reasoning Tool

Uncertainty is associated with any reasoning system and it comes from a variety of sources. Reliability of the information, ambiguity and vagueness within the representative language, incompleteness of the information, and imprecision in aggregation of the information from multiple sources are but a few examples. Zadeh (Ref. 18) maintained that the ability of humans to extract the important items out of a mass of information is derived from a human tendency to think approximately. In other words, human thinking involves a gradual transition from membership in a class to non-membership in a class rather than an abrupt change between classes.

For example, most people would agree that a person 6'-6" in height is "tall." They would probably also agree that a person 5'-6" in height is "not tall." How then do we classify a person who is 5'-11" in height? Obviously, the class of "tall" people is not a "crisp" set, and, thus, there is a gradual transition from being a member of the class and not being a member of the "tall" class. This is naturally how humans think.

Because most of the knowledge in an expert system is obtained from human experts and because much of human language and knowledge is vague, it is usually true that facts and rules are neither totally certain nor totally consistent. Because of this, we may describe the reasoning process used by experts in certain situations as approximate. In this report, the theory of fuzzy sets is used to help assess uncertain information derived from this approximate reasoning process.

In any given language, the values of a linguistic variable are words, phrases, or sentences. For example, structural damage can be considered as a linguistic variable with values such as "severely damaged," or "moderately damaged." These are meaningful classifications but not clearly defined. With the use of fuzzy sets, however, we can quantify such terminology and apply it in a meaningful way to help solve a complex problem. An evident advantage of

the fuzzy set approach is the possibility of representing numeric and linguistic variables in a uniform way and of using a formalized calculus to manipulate these variables. Simply defined, fuzzy set theory is a theory of the mathematics of approximate reasoning.

Although the process of fuzzy reasoning is expressed using mathematical equations, it is not a statistical method. It is an approximate reasoning process which is compatible with human intuition. The advantage of the fuzzy reasoning is that it can yield an approximate answer even when there is not sufficient information to support a statistical method. The notion of probability stems from, and depends on, the idea of repeated trials. Under identical and repeatable laboratory conditions conducted on simple models, this probabilistic notion readily applies; but, in real-world (in particular human) systems, experiments are rarely identical and repeatable. Therefore, for the subjective assessment of complex systems, probability has its limitations.

Fuzzy Sets Defined By Example

The vagueness or uncertainty as to whether an object belongs to a class or set is a question of membership. In classical set theory, an element is either within the domain of the set, or it is not. Mathematically, this binary notion of set membership is handled with the indicator function. In fuzzy set theory, the degree of membership of an element x in a set A, denoted $\mu_A(x)$, can be any value in the interval [0,1]. For instance, if the membership level is one, then the item or object is definitely a member. If the membership level is zero, then the item is definitely not a member. If the membership value is between 0 and 1, then the value stated indicates the belief that the object is a member of the set.

In fuzzy set theory, the set A can be represented in terms of its membership function as follows.

$$A = \frac{\mu_A(x_1)}{x_1} + \frac{\mu_A(x_2)}{x_2} + \dots + \frac{\mu_A(x_n)}{x_n} = \sum_{i=1}^{n} \frac{\mu_A(x_i)}{x_i}$$

where each x_i is an element of the set A. When x is a continuous variable,

the set A is denoted:

$$A = \int \frac{\mu_A(x)}{x}$$

where the symbol "——" is a delimiter which denotes the association of the membership value $\mu_A(x_i)$ with the element of A, and the symbols "$\int$" and "+" denote the union of all elements of the fuzzy subset in the continuous and discrete case, respectively. As an example, suppose the set A represents tne universe of discrete concrete strengths:

$$A = [2.0,\ 3.0,\ 4.0,\ 5.0,\ 6.0,\ 7.0]\ (k/in^2)$$

Then, for this example, the x_i are the discrete values of concrete strength. A moderate strength concrete may be expressed in fuzzy terms as:

$$\text{"Moderate Strength"} = \left[\frac{0.0}{2.0} + \frac{0.2}{3.0} + \frac{0.8}{4.0} + \frac{1.0}{5.0} + \frac{0.5}{6.0} + \frac{0.0}{7.0} \right]$$

In other words, this expression means that 5.0 k/in^2 concrete is definitely a member of the set "moderate strength," 2.0 and 7.0 k/in^2 are definitely not members of the set "moderate strength," and 3.0, 4.0, and 6.0 k/in^2 concrete are somewhere in between in terms of membership. A classical representation using crisp set theory could be expressed as:

$$\text{"Moderate Strength"} = \left[\frac{0}{2.0} + \frac{0}{3.0} + \frac{1}{4.0} + \frac{1}{5.0} + \frac{1}{6.0} + \frac{0}{7.0} \right]$$

The difference between a "fuzzy" representation and the "classical" representation of "moderate strength" is illustrated in Figure 15.

The construction of a membership function is a straightforward task that can be accomplished with the cooperation and assistance of a panel of experienced engineers or experts in the specific field. The resulting membership functions can then be manipulated in a logical manner to obtain an answer to a complex problem.

The presentation of the mathematics of the fuzzy set theory is beyond the scope of this report. For more detail, the reader is referred to any of References 9,18,19,20,21,22, and 23.

Multiple Attribute Decision Analysis

In most engineering problems, there are typically many solutions or alternatives available to the engineer for solving a problem. In order to choose the most optimum solution to the problem, the engineer must have a method by which to assess and compare each of his alternatives. One such method is outlined here. The usefulness of this analysis procedure will be explained in a subsequent section.

First, we denote the alternatives available to the decision maker as A_1, A_2,...A_n. For each of these alternatives there may be several criteria (relevant to each alternative) available for evaluation. Each of these criteria, in turn, are given some degree of linguistic rating, denoted r_{ij}, such as "bad," "good," "very good," etc. Furthermore, each of these criteria has an importance factor (i.e., not all criteria are equally important). We can represent the importance of a criterion with a linguistic weighting term, w_j. The relationship among these linguistic parameters can be seen in Table 11.

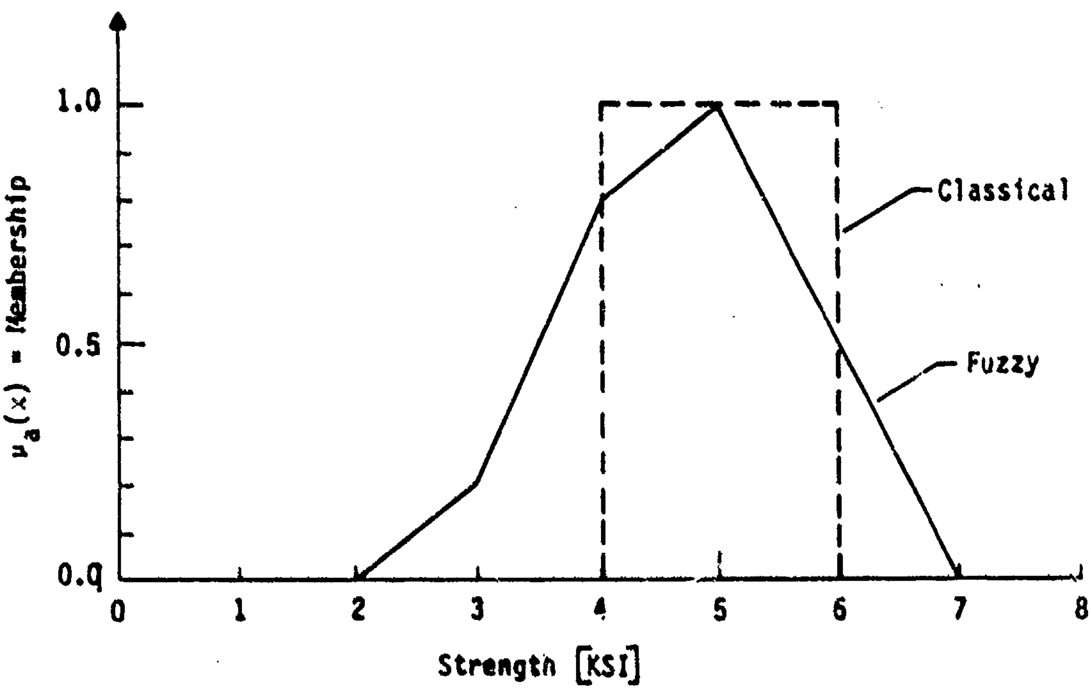


Figure 15. Classical and fuzzy representations of a moderate strength concrete.

TABLE 11. EXAMPLE RATINGS AND WEIGHTS FOR DECISION ANALYSIS (modified from Ref. 6).

	Importance of criterion (weight) $= w_j$	Ratings $= r_{ij}$	
		Alternative 1 A_1	Alternative 2 A_2
Criterion (aspect) 1	$w_1 =$ Very important	r_{11} = Good	r_{12} = Fair
Criterion (aspect) 2	$w_2 =$ Rather unimportant	r_{21} = Fair	r_{22} = Good

Assuming that the linguistic terms r_{ij}, and w_j, can be quantified, the following equation can be used to determine a weighted average rating for each of the alternatives:

$$\text{Rating for } A_i = \frac{\sum_{j=1}^{n} w_j \cdot r_{ij}}{\sum_{j=1}^{n} w_j} \qquad (4)$$

where n equals the number of criteria. Finally, by calculating this rating for each of the alternatives, the relative merits of each may be compared to help produce an optimum decision.

Dong et al. (Ref. 20), have derived an efficient computational method, called the DSW algorithm, by which fuzzy sets are integrated into this multiple-attribute decision process. The linguistic terms associated with the ratings (r_{ij}), and the importance weightings (w_j) are assigned fuzzy set representations. The calculation of ratings for each alternative is done with Equation 4, using fuzzy logic equivalents of addition, subtraction, multiplication, and division. The algorithm is well suited for computer implementation.

The usefulness of this algorithm will be examined later where it will be shown how the DSW algorithm can be effectively used to combine the subjective information outlined in Section III into a preliminary decision relating modes of structural response to degrees of damage.

ORGANIZATIONAL STRUCTURE

Overview

In the introduction to this report, it was stated that the objective of this work was to study and develop a computer code to be used for the damage assessment of protective structures. In Sections I, II, and III the problem was introduced, and the available information for possible inclusion into the code was reviewed. In earlier subsections the "tools" used to synthesize all this information were discussed briefly. The purpose of later subsections

will be to show how all this material is combined to create the present version of the DAPS code (Damage Assessment of Protective Structures).

As discussed previously, the major factors influencing an assessment of the buried box structure included structural integrity, functionality, and repairability. Given sufficient information, it would be possible to determine three separate damage level assessments of the structure, one from each factor. If each of these assessments is then given a weighting or importance value by a decision maker, a final analysis of the level of damage to the structure can be computed using a method similar to the one outlined previously. The ultimate goal, therefore, is to take the assessment from each of these factors and to combine them into one meaningful assessment. This procedure is represented in Figure 16.

The organizational structure developed to accomplish this task is shown in Figure 17. The level of damage from each of the three factors can be provided using an expert system approach. In this particular case, each of the factors could be developed as a separate module within the expert system architecture. Using the expert system shell EXSYS as the inference mechanism and knowledge base, assessments for structural integrity, functionality, and repairability can be calculated, and the information shared and stored. With analyses completed, the information in the form of fuzzy sets is passed to an external program, where a DSW algorithm is activated to combine the assessments. Only the structural integrity module of Figure 17 was developed for this report.

The logical flow of the structural integrity module is outlined in Figure 18. There are three major parts to this module as follows: (1) Rules concerning total failure, (2) Rules concerning soft (subjective) data, and (3) Rules concerning hard (objective) data. The first part of the code deals with the trivial case of total failure of the structure, i.e., roof collapse. For this particular case, several rules were developed from the questionnaire sent to the experts (rules 1-9 in Appendix C). If total failure has occurred, these rules are activated, and the mode of failure is determined. The level of damage is set to total failure, and the remainder of the structural integrity module is bypassed. An example rule follows.

(a) Damage level assessments:

$[B]_{3x1} =$

	Damage level
Structural Integrity	Moderate
Functionality	Slight
Repairability	Severe

(b) Weighting or importance matrix:

$[A]_{1x3} =$

Structural integrity	Functionality	Repairability
Important	Very important	Less important

(c) Ultimate goal:

Final answer: $[A] \times [B] = [C]$

$[C]_{1x1}$ = Overall damage

Damage level
Moderate

Figure 16. Representation of structural damage assessment goal.

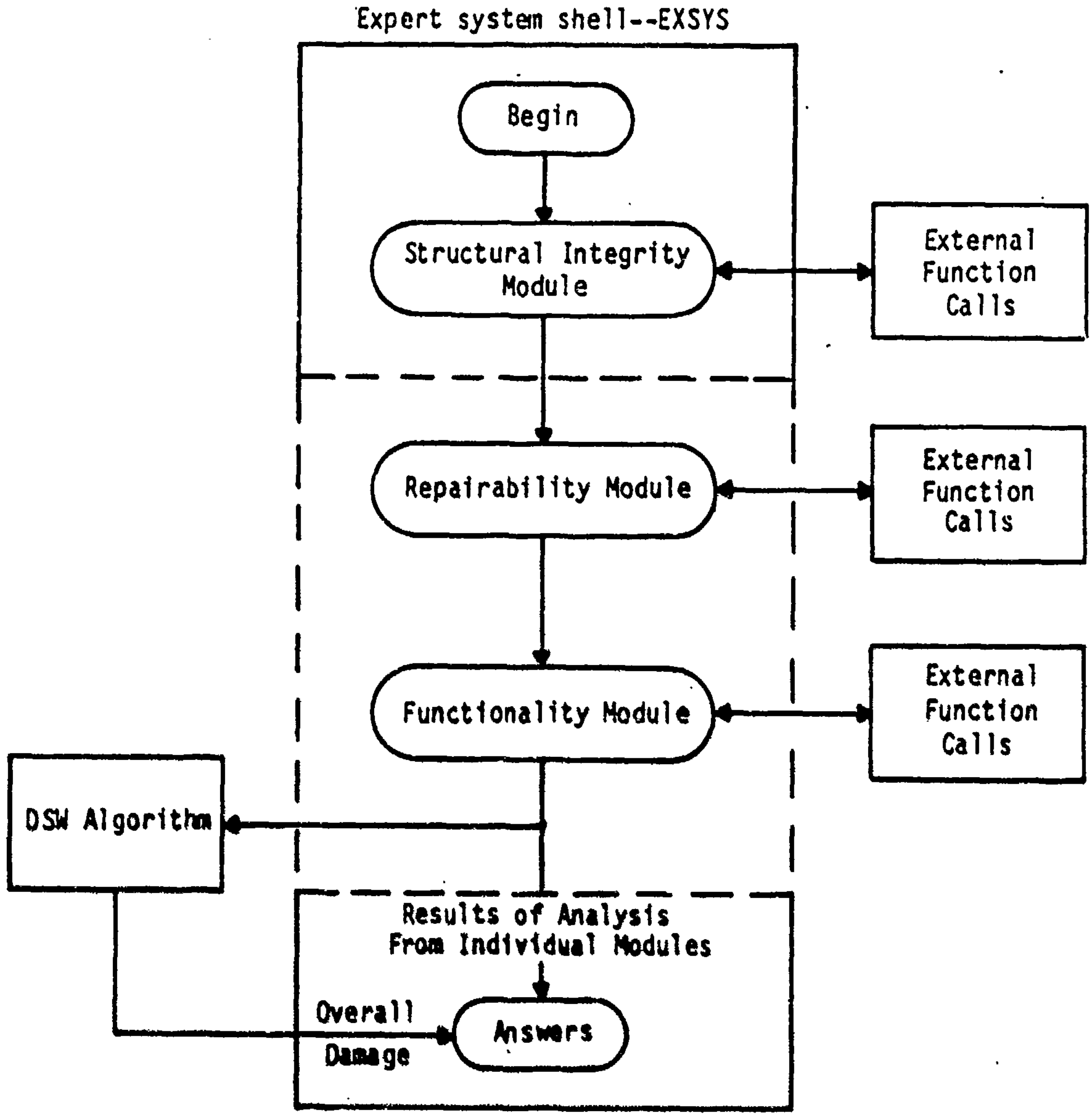


Figure 17. Organizational structure of DAPS.

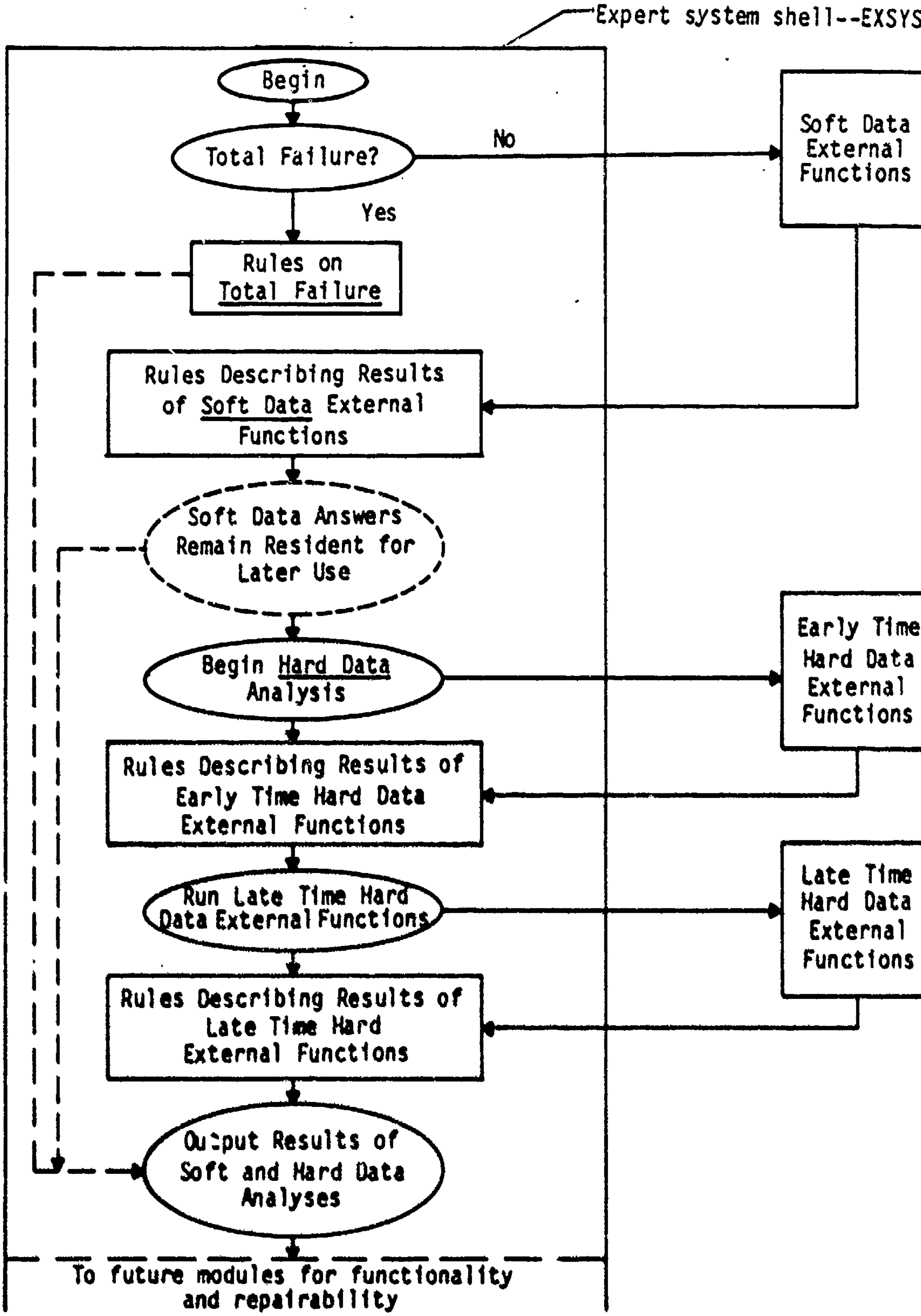


Figure 18. Logical flow of structural integrity module.

RULE NUMBER: 5

IF:

complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)

and the failure has occurred at the slab-wall connection

and the separated slab is lying flat on the floor (implying a symmetric failure)

and the failure surface(s) at both supports are relatively rough with many cracks and "concrete teeth"

and inspection of the failure region indicates the main reinforcing bars exhibited rupture after significant deformation (note "necking" or stretching)

THEN:

damage level as determined by structural integrity analysis from visual information is total failure - Probability=1

and the mode(s) involved in the deformation process as determined by visual (subjective) information were predominantly shear and diagonal tension, causing rupture of reinforcement after significant rotation and deformation. It is possible that the failure region was underreinforced - Probability=1

and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

The second and third parts of the module deal with the subjective and objective data respectively, as outlined in Section III. Because these two parts encompass the major effort of this report, the methodology used to develop and implement these two parts will be discussed in later sections.

Structural Integrity Analysis Using Soft Data

Derivation of Analysis Procedure. When the data from the expert questionnaires were analyzed, it was originally intended that this information would be codified into the computer in typical expert system fashion, i.e., in the form of IF-THEN production rules. Upon further investigation, however, it was found that this could not be accomplished easily. The reason for this is due to a combinatorial explosion. In most expert systems, the whole purpose of a rule base approach is to use intuitive logic in the form of production rules to "prune" the number of paths or combinations available for solving a complex problem. In the case under study, the number of possible structural attribute combinations (and therefore number of rules) is simply much too large to be handled in the normal manner.

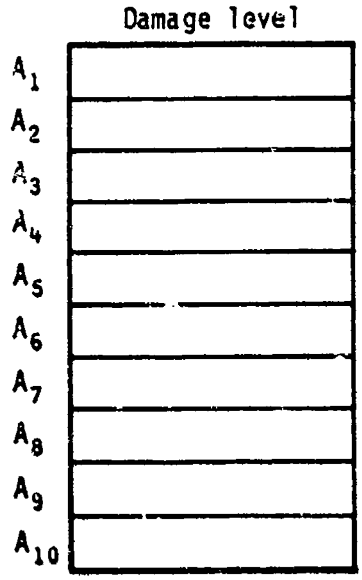
To illustrate this, assume that each of the structural attributes listed in Table 9 can attain one of six degrees of damage; none, slight, moderate, severe, very extensive, or unknown. Since there are 10 attributes, the number of possible combinations for the full space is $6^{10} = 60,466,176$. Obviously, even though all these combinations are mathematically possible, most of them would have no real physical meaning in terms of describing the modes of response of the structure. The point of the illustration is this; the complexity is such that, to describe all possible responses, the number of rules required renders the problem intractable.

Although this large attribute-damage space could be pruned using production rules, the expertise needed to develop these rules is not available. However, it is possible to circumvent this problem using a fuzzy logic approach. To accomplish this, we found that there existed two very useful conceptual relationships within the expert data which could be expressed in matrix form. The first matrix, which will be denoted the user matrix [U], is shown in Figure 19a. The ten rows represent the ten structural attributes identified in Table 9. The ten slots in this matrix are filled by user response during a session as follows. Given some type of visual data (photographs, visit to site, etc.) of a damaged structure, the user chooses one of six degrees (none, slight,...unknown) that best describes the level of damage of each structural attribute. For example, A_1 might be slight, A_2 might be severe, A_3 might be none, and so on. For each linguistic term, there is a corresponding fuzzy set representation.

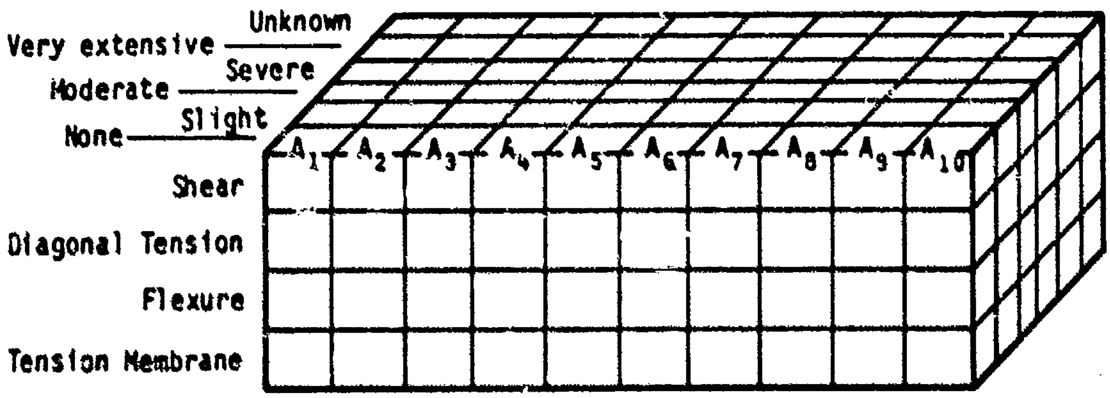
The second matrix relationship, denoted [E] in Figure 19b, is slightly more complex and, thus, must be carefully explained. This matrix is termed the expert matrix because the relational contents are derived from expert opinion. In Figure 19b, the [E] matrix is shown to be three-dimensional. Each row represents a major mode of response, each column a structural attribute, and the third dimension normal to the page represents the six degrees of damage attainable by each structural attribute. Thus, each slot in the (A_i x Mode) space represents the relationship between a given mode and a given attribute which has achieved a given degree of damage. Careful study of the expert reasoning process showed that most experts' judgments of the relationship between a mode and an attribute depend on the degree of damage attained by that attribute.

(a) [U] Matrix produced by user input:

A_i = ith Structural attribute



(b) [E] Matrix produced by expert opinion:



(c) Product of [E] x [U] = [P]:

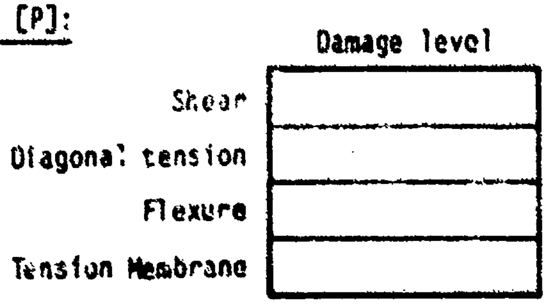


Figure 19. Matrix relationships for subjective information.

For instance, take the first slot in the upper left-hand corner of Figure 19b. Given that attribute A_1 is none (with respect to damage), an expert might determine that there is no relationship between shear and attribute A_1. Obviously, the relationship can vary between no relationship (i.e., attribute A_1 has nothing to do with a shear mode response) and complete relationship (i.e., shear mode response is significantly dependent on the degree of attribute A_1). Since the idea of relationship is a continuous function between no relationship and complete relationship, the use of fuzzy sets to represent these vague terms is ideal. Figure 20 shows a typical fuzzy set representation of no relationship for the example above.

Given that the [U] matrix is filled by user response, and the [E] matrix is filled by expert opinion, the two may now be combined to produce an analysis of the damaged box. The process used to combine the two matrices is the DSW algorithm discussed previously. In this case, however, the criteria are the structural attributes, the ratings are the values given in [U], and the weightings are the values given in [E]. Using the DSW algorithm, the

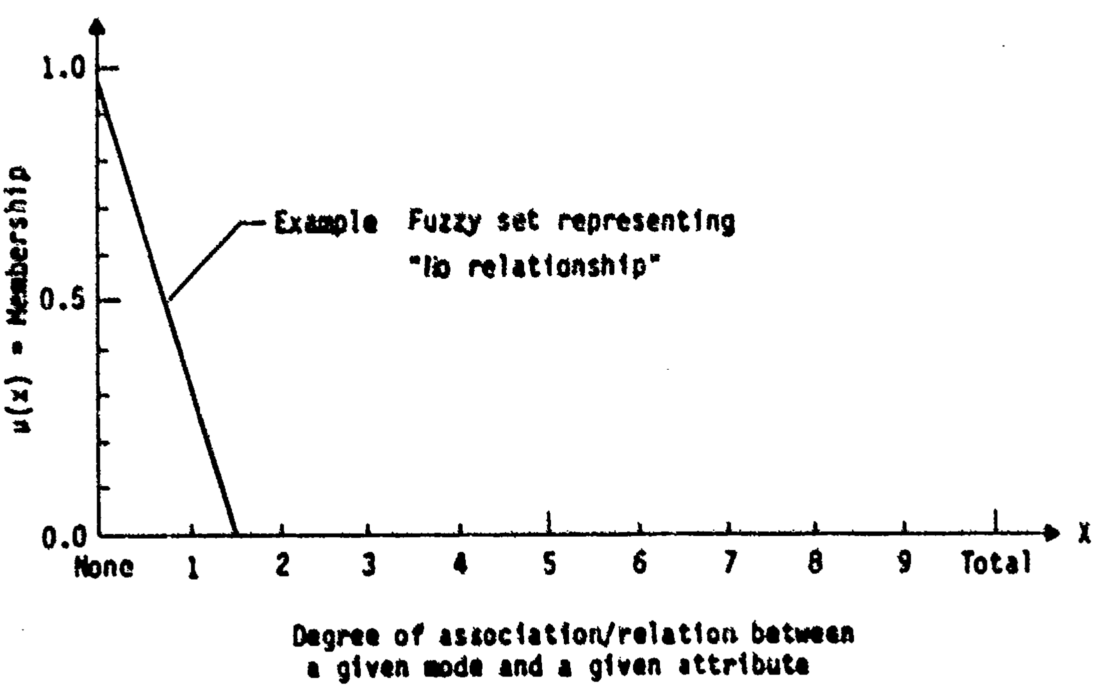


Figure 20. Example fuzzy set representing "No Relationship" between a shear mode and structural attribute A_1.

damage level of the structure associated with each of the four modes can be calculated using Equation 5.

$$(\text{Damage Level})_i = \frac{\sum_{j=1}^{10} E_{ij} \cdot U_{ij}}{\sum_{j=1}^{10} E_{ij}} \qquad (5)$$

It is important to remark here that although the [E] matrix is three-dimensional conceptually, when used in the calculation process, it has been reduced to a two-dimensional matrix. This reduction process results when the user chooses one of the six levels of damage for each of the structural attributes. By doing so, the other five columns (in the third dimension of Figure 19b) for each attribute are eliminated. In other words, only one column in the third dimension is used for each attribute.

Once [E] has been reduced to a two-dimensional matrix, it may be combined with [U]. The result of this operation is a 4x1 matrix denoted [P], as shown in Figure 19c. Each slot of [P] is a fuzzy set describing the level of damage associated with the given mode of damage.

Before continuing on with an explanation of how the results of this process are interpreted, an explanation of how fuzzy sets are chosen for linguistic terms is necessary. Because the linguistic terms themselves are vague, the choice of shape(s) used to describe these terms is also rather arbitrary. In the literature, the shapes most often chosen include the triangle and the trapezoid. Shapes with other than straight lines may be chosen, but complexity in mathematical manipulation makes them very undesirable. For this study, the fuzzy sets chosen to describe degrees of damage are shown in Figure 21. Typically, the shapes and their locations in the universe of discourse (abscissa axis) are decided by consensus of expert opinion.

In particular, the reader should notice the fuzzy set representing the linguistic term "unknown." After much debate and many trial shapes and calculations with these shapes, a rectangle (unit membership throughout) was chosen. Upon reflection, this shape appears to be the most intuitive choice. The very idea of an "unknown" damage level implies that it could be anywhere

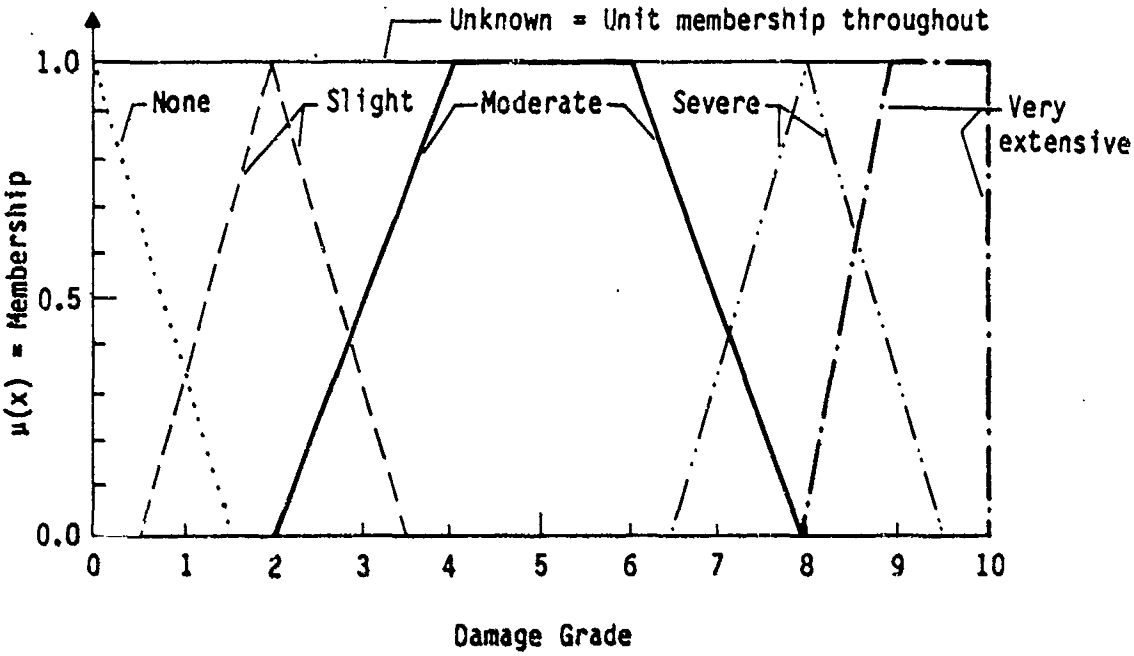
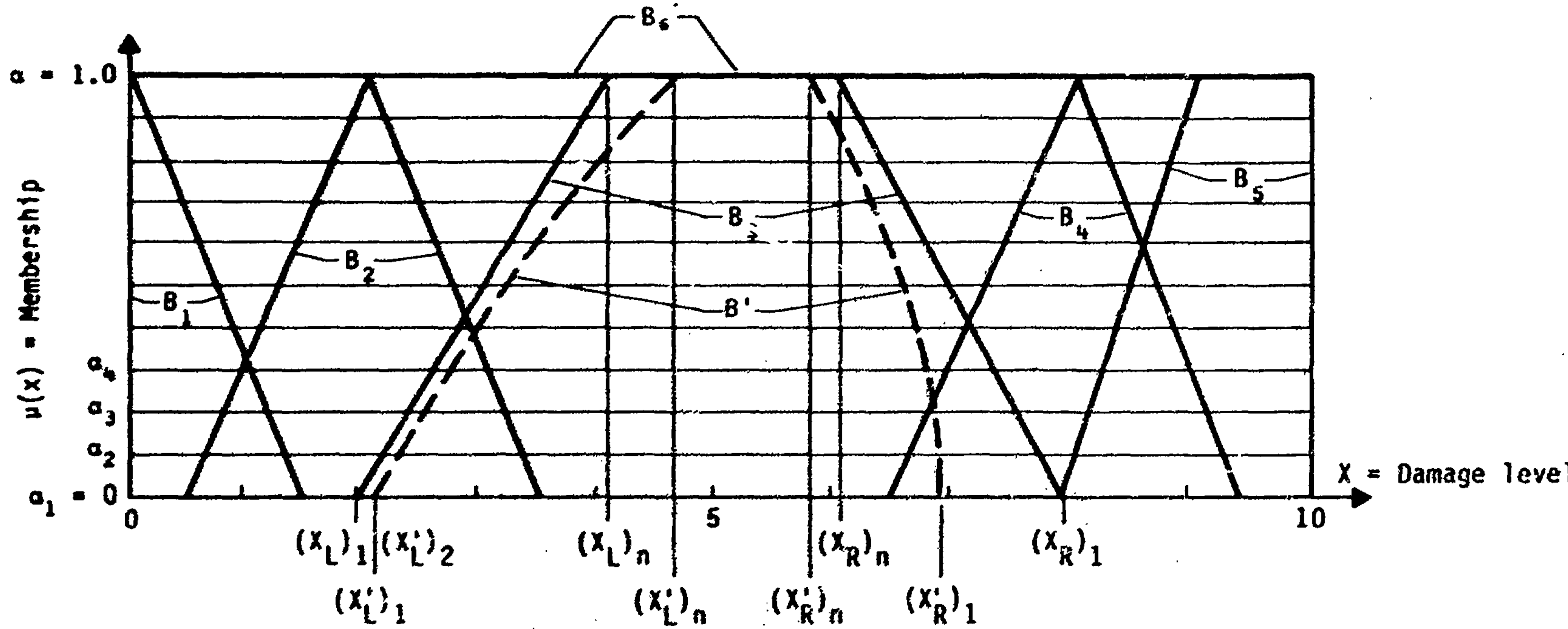


Figure 21. Fuzzy sets representing linguistic damage levels.

between "none" and "very extensive." The implication of including unknown into a calculation is to extend the resulting answer in both directions, i.e., toward "none" and toward "very extensive." Thus, the addition of "unknown" into an analysis lends more uncertainty to the answer, just as it should.

The interpretation of the calculated fuzzy sets is a difficult task. Ideally, the goal is to find a linguistic term that corresponds to each calculated fuzzy set. Because of the nature of the weighted average algorithm, however, the actual shapes of the resulting fuzzy sets may not be as neat and symmetrical as the fuzzy sets used to produce them (i.e., triangles, trapezoids, or delta-functions). If we superimpose a typical calculated fuzzy set onto the universe of fuzzy sets representing the different damage levels as shown in Figure 22, it is possible to make a comparison between the shape of the calculated set and each of the predefined damage level sets. One way of comparing fuzzy sets is to use a difference measure, denoted D. If the value of D between the calculated fuzzy set and one of the predefined sets is small, then it is possible to say the sets are similar. In the case of good similarity, the linguistic term for the predefined fuzzy set may be applied to the calculated fuzzy set.



B' = Calculated Damage Level

B_1 = No Damage

B_2 = Slight Damage

B_3 = Moderate Damage

B_4 = Severe Damage

B_5 = Very Extensive Damage

B_6 = Unknown Damage

Figure 22. Calculation of difference measure.

The difference D can be measured by a number of techniques, some of which were examined for this study. The difference measure chosen is a modified Euclidean approach and is given by Equation 6. This measure was chosen because it was most easily adapted to the DSW algorithm, and because it provides a relatively good measure of similarity between a predefined fuzzy set and a calculated fuzzy set. In this context, similarity is meant to describe both "similarity of shape" and "distance between" the predefined and calculated fuzzy sets.

$$D = \sqrt{\sum \left[(X'_L)_i - (X_L)_i \right]^2 + \left[(X'_R)_i - (X_R)_i \right]^2} \tag{6}$$

where

n = number of α-cuts

$i = 1, 2, \cdots 10$

$(X'_L)_i$ = Left-hand damage level value at the i^{th} α-cut level of B'

$(X_L)_i$ = Left-hand damage level value at the i^{th} α-cut level of B_i

$(X'_R)_i$ = Right-hand damage level value at the i^{th} α-cut level of B'

$(X_R)_i$ = Right-hand damage level value at the i^{th} α-cut level of B_i

The modification to the Euclidean approach involves the use of the α-cut interval method, which forms the basis of the DSW algorithm. As we see in Figure 22, α-cuts are simply parallel horizontal lines of constant membership that cut through the fuzzy sets. The intersection of these lines with a fuzzy set identify points on the universe of discourse which have the same membership value.

Using Equation 6, it is possible to calculate the difference measure, D, which is a measure of the difference between the calculated fuzzy set and each predefined fuzzy set. The linguistic term chosen for the calculated fuzzy set is simply the linguistic term corresponding to the predefined fuzzy set with the lowest D (i.e., highest similarity). Although this is probably not the most rigorous or elegant method available for determining similarity, for demonstration purposes, it provides a good indication of <u>relative</u> similarity.

Explanation of External Programs Used in Soft Data Analysis

The previous discussion was focused on describing the methodology used in combining subjective expert opinion with observed structural damage provided by the user of the code. In this section, the focus will be on presenting the manner in which this information was coded into the computer. As was shown in Figure 18, the code begins by determining if complete failure of the structure has occurred. If true, the code proceeds as discussed previously. However, if the answer is false, a series of calls to external programs is made by EXSYS in order to begin processing the soft data. There are four external programs used in the soft data manipulation process, as shown in Figure 23. All external programs were written in either FORTRAN or BASIC computer languages. Programs written in BASIC were done solely because of the extensive graphics capabilities available in the language. Each of the four programs will be discussed next.

Program FUZSET. The program FUZSET is the first program to be called from EXSYS. This portion of the code is written in BASIC and is composed of two major sections. The first section of the program presents graphic pictures of the fuzzy sets that will represent the linguistic terms none, slight, moderate, severe, very extensive, and unknown, similar to Figure 21. These fuzzy sets were predetermined by the authors and are stored in the data file USER.DAT. During the presentation of these fuzzy sets, the user is given the option of viewing or changing their shapes if he/she is uncomfortable with the current defined shape.

The second section of the program deals with the user matrix [U] and the expert matrix [E] described previously. It is at this point in the code that the computer questions the user about the ten structural attributes listed in Table 9 (assuming they have access to the information). During this question and answer period, the user also has the option of viewing the fuzzy relationships in the expert matrix [E] dealing with the attribute about which they are being questioned. The purpose of this is that it may aid them in their decision making process. As an added option, the user may also change the relationships in the [E] matrix if they are unsatisfied with expert opinion on a given mode/attribute relationship. All fuzzy sets are stored in data files as shown in Figure 23.

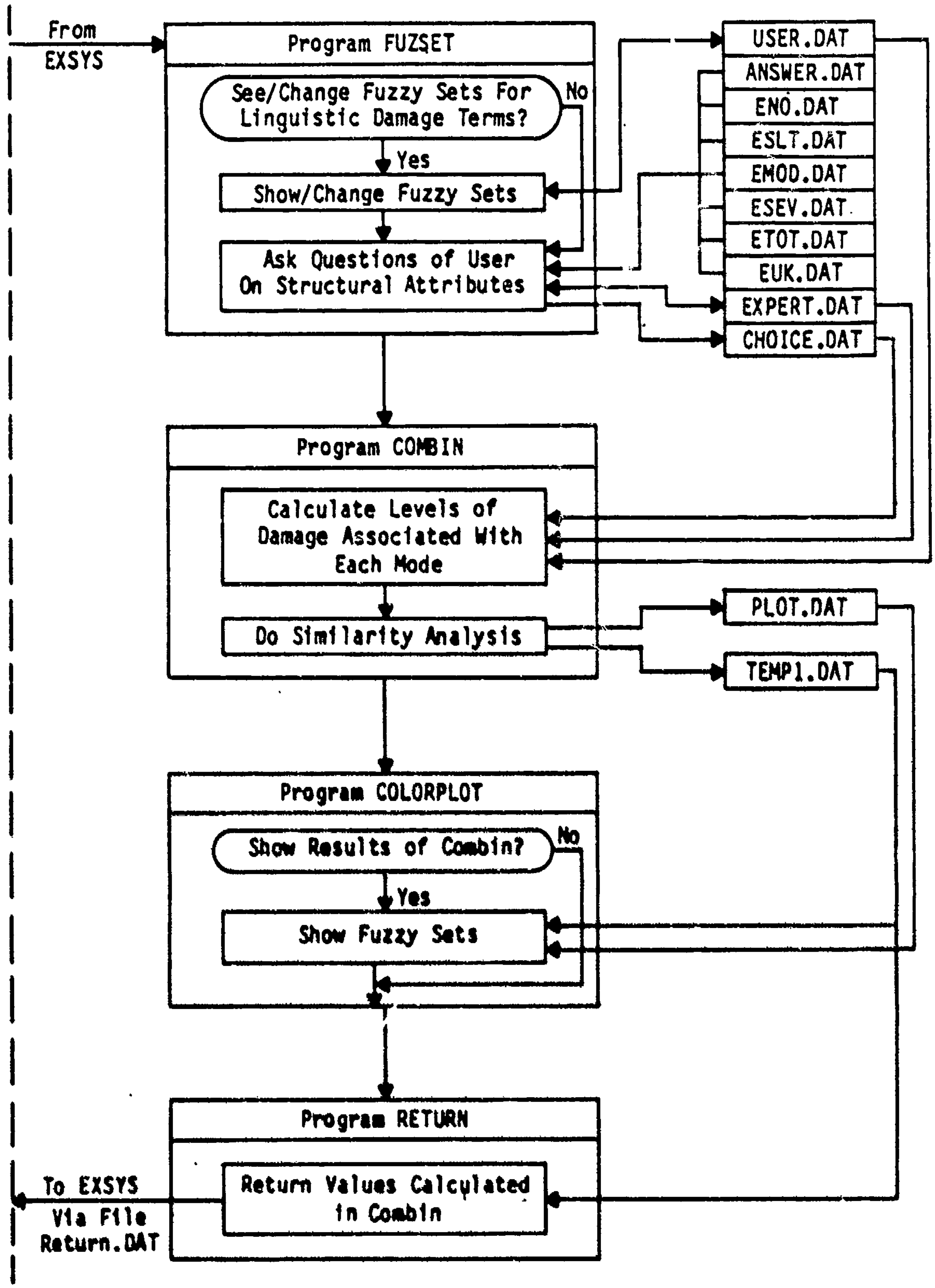


Figure 23. Organization of soft data external functions.

Program COMBIN. The program COMBIN is a program written in FORTRAN and has no direct interaction with the user. COMBIN is called immediately upon completion of the program FUZSET, and its major purpose is the combination of information derived from the user in FUZSET. This combination process is accomplished through the use of Equation 5 which outputs four fuzzy sets. Again, these four fuzzy sets represent the level of damage of the structure associated with the four modes of response. After the DSW algorithm has been completed, a similarity analysis is performed on each calculated fuzzy set using Equation 6. Thus, a linguistic term is applied to each mode of response. Of these four linguistic descriptions, the term describing the highest level of damage becomes the overall damage indicator of the structure as determined by subjective data.

Program COLORPLT. The BASIC program COLORPLT is run by EXSYS after all calculations in COMBIN have been completed. The function of COLORPLT is quite simple -- to present to the user a graphical representation of the results obtained in the program COMBIN. The user is asked if he/she would like to view the results. If yes, the program is run; if no, EXSYS continues without executing COLORPLT.

Program RETURN. As seen in Figure 24, the sole function of program RETURN (written in FORTRAN) is to transfer to EXSYS answers obtained in all external programs. The values obtained in COMBIN are placed in a temporary data file called TEMP1.DAT. RETURN simply reads these values and returns them to EXSYS via file RETURN.DAT, as explained in Appendix B. Five values are returned to EXSYS in this manner, the first four representing the damage associated with each mode, and the fifth representing the overall damage of the structure.

Once the values have been passed to EXSYS, there are several rules (rules 13 to 42 in Appendix C) which provide a linguistic interpretation of the modes and damage levels computed by the program COMBIN. An example rule follows.

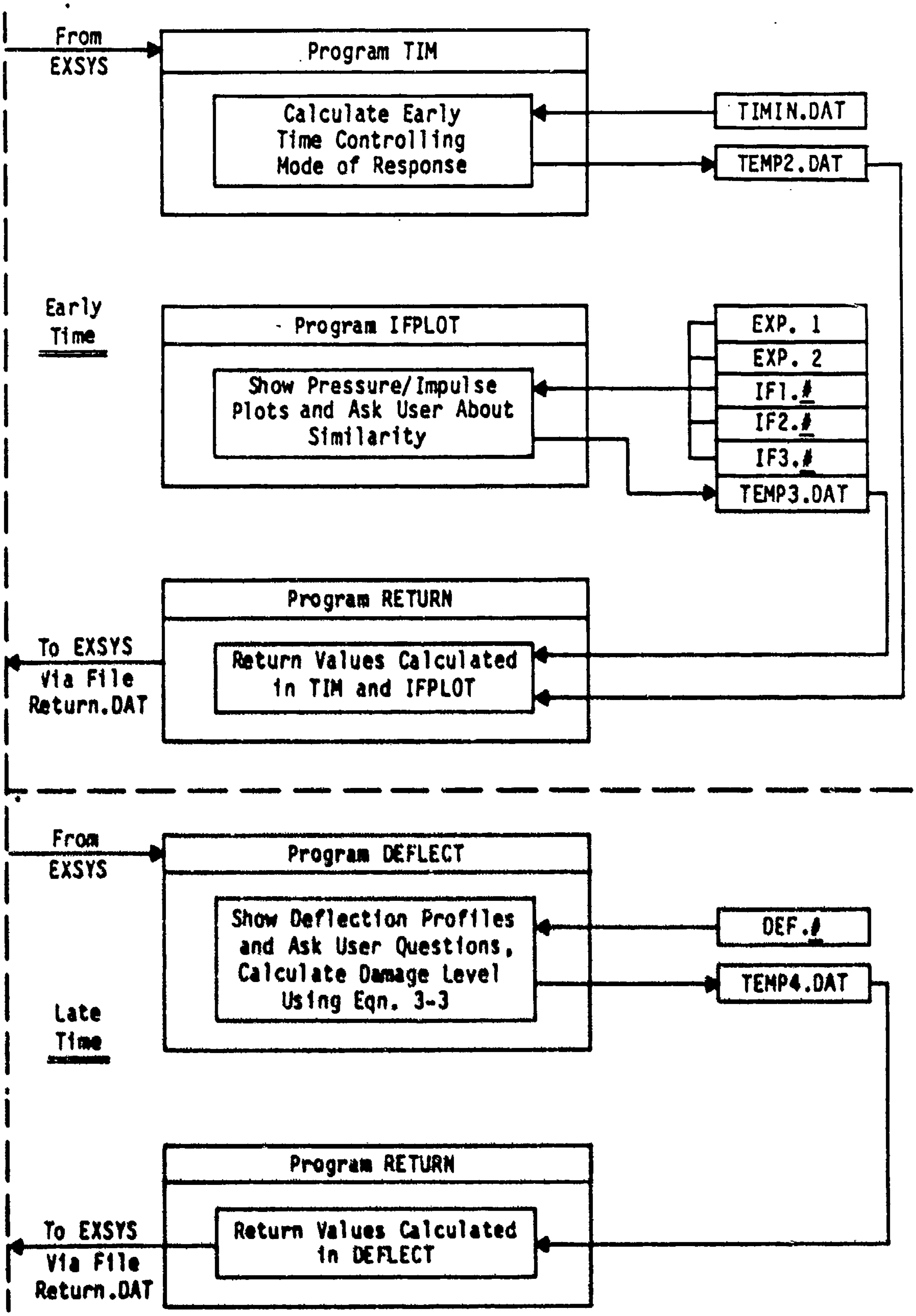


Figure 24. Organization of hard data external functions.

RULE NUMBER: 27

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and flexure damage is moderate

THEN:

the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

This information not only is output at the end of an EXSYS run but can be used later in the code as a priori knowledge in rules dealing with the functionality and repairability of the structure.

Structural Integrity Analysis Using Hard Data

Having completed the analysis of the soft data, the code proceeds to the hard data portion, as shown in Figure 18. In the soft data analysis just discussed, the information used was derived from "extremely late-time" data, i.e., posttest observations. On the other hand, all available data to be used in the hard data analysis corresponds to structural responses occurring between 0 and 15 ms after initial loading. Nevertheless, the hard data analysis described in this section will be assigned to two segments, one based on early-time analysis and one on late-time analysis.

The reasoning for these separate sections is based on the previous discussion of the hard data. In that section, it was pointed out that not all data are of equal value in determining modes of response at different points

in time. Interface pressures, for example, give a good indication of early-time (less than approximately 2 ms) slab response, whereas deflection profiles give a good indication of late-time (greater than approximately 2 ms) slab response. The early-time analysis is important because it provides an indication of trends in response. Thus by knowing the early response first, late-time analysis (from deflection profiles) and overall response modes may be better understood and interpreted.

Therefore, in the next subsection the techniques and external programs used to calculate "early-time" response will be discussed. In the following subsections the methodology used to provide "late-time" analysis is discussed, as well as the rules used to combine both analyses into an overall "hard" assessment of the structure.

Early Time Analysis

The calculation of the early-time response of the structure in DAPS is limited to two programs external to EXSYS. These two programs, TIM and IFPLOT, are illustrated in the top half of Figure 24, and an explanation of each is given below.

Program TIM. Program TIM is a FORTRAN code developed by Mickelsen (Ref. 24), which determines the early time response of a fixed-fixed beam using a Timoshenko beam model. The computer program first solves for the natural frequencies of the Timoshenko beam model. These natural frequencies are then used in a modal analysis to obtain the response characteristics of the beam. The purpose of the program is to determine the controlling early time response mode of the structural element. This is accomplished by determining the times at which the support shear and support bending moment reach their ultimate capacities. Whichever force exceeds its capacity first, controls the early time response.

The fixed-fixed beam model is used because it represents very well the one-way, early-time response of the roof slab in the buried box structure (Ref. 7). The inputs to the program include material, geometrical, and loading parameters of the box structure under study. These parameters are obtained interactively from the user before the program TIM is executed. The output of the program is a value equal to either 0 or 1, representing a direct

shear or flexure mode respectively. The value is written to the temporary data file TEMP2.DAT for later use, as shown in Figure 24.

Program IFPLOT. Program IFPLOT is a BASIC program whose function is to determine the similarity of interface pressure records as discussed previously. The program begins by showing the user the superimposed interface pressure records and corresponding impulse plots of the structure under study. The user is then presented with a question concerning the similarity of the superimposed plots. Because this question involves a large amount of subjectivity, the user is allowed to view example plots representing two possible responses. The user is also allowed to toggle between the question, example plots, and actual plots as desired, before making a decision. As discussed earlier, the purpose of this comparison is to determine whether the early-time response falls into the category of shear, flexure, or shear-flexure. The output of IFPLOT is a value between 1 and 3 (shear = 1, flexure = 2, shear-flexure = 3), representing each of the possible modes, and is stored in the temporary data file TEMP3.DAT.

With programs TIM and IFPLOT completed, the data obtained from these analyses are transferred back to EXSYS via the program RETURN. Within EXSYS, the data from TIM and IFPLOT are linguistically interpreted in rules 45-48, providing an assessment of early-time response. An example rule follows.

```
RULE NUMBER: 45

IF:
     complete failure of the structure is false (i.e., the roof slab has not
     been completely separated from one or both of its supports)
and  early time response as determined by modified Timoshenko beam analysis is
     shear
and  early time response as determined by similarity analysis of interface
     pressure plots is shear

THEN:
     early time response as determined by a combination of Timoshenko beam
     analysis and interface pressure data is predominantly shear -
     Probability=1
```

In the case of conflicting answers from the two programs (e.g., shear and flexure), the response is assumed to be a combination of both. Therefore, unless both TIM and IFPLOT produce the same answer (i.e., both shear or both flexure), the early-time response is termed shear-flexure. This conclusion simply implies that there is no overwhelming evidence to substantiate one dominating mode. This information is used later to help determine the late-time response of the structure.

Late Time Analysis

The calculation of late-time response of the structure in DAPS is done in the external program DEFLECT, as shown in the bottom half of Figure 24. An explanation of this program follows.

Program DEFLECT. DEFLECT is a program written in BASIC. It shows the user the deflection profiles of the underside of the roof slab at 3 ms and 15 ms. The usefulness of deflection data in determining modes of response was presented earlier and is implemented in DEFLECT. Only two deflection profiles were used to illustrate the concept of late-time analysis. Other deflection profiles at different times could have been used just as easily.

After viewing the deflection profiles, the user is asked three questions (Fig. 25) concerning the magnitude of deflection at the centerline and deflection ratios calculated at the wall, quarter point, and centerline. To aid the decision process, the user is allowed to toggle between questions and profiles in order to study them more carefully. Because the questions are somewhat subjective, numerical limits on linguistic terms (e.g., "very small deflection" is approximately 0.5 in) are given to aid the user in his/her response.

The damage level of the structure as determined by objective information is also calculated within the program DEFLECT. Using Equation 3, the deflection profile for 15 ms is numerically integrated to provide a measure of overall damage. The value calculated by Equation 3, along with the answers to the three questions, are stored in a temporary data file, TEMP4.DAT, as shown in Figure 24.

Question 1

The deflection (at 15 ms) of the roof slab near the wall (2 1/2 in from face) is 5.5 in. Typically, when evaluating modes of response (especially shear), a near-wall deflection in the range of

- < 0.5 in is considered very small.
- 0.5-1.5 in is considered small.
- 1.5-3.0 in is considered moderate.
- > 3.0 in is considered large.

In your opinion, given this information and the deflection profile, which category do you think the given deflection of 5.5 in belongs?

1. Very small
2. Small
3. Moderate
4. Large

Enter a value of 1-4, or just ENTER to view plot?

Question 2

At 15 ms, the ratio of differential deflection (near-wall deflection minus centerline deflection) to slab thickness is 0.28. Typically, when evaluating modes of response (especially flexure and tension membrane), a ratio in the range of

- < 0.3 is considered in relatively flat.
- 0.3-0.6 is considered moderately curved.
- > 0.6 is considered highly curved.

In your opinion, given this information and the deflection profile, which category do you think the given ratio of 0.26 belongs?

1. Relatively flat
2. Moderately curved
3. Highly curved

Enter a value of 1-3, or just ENTER to view plot?

Question 3

At 15 ms, the ratio of differential deflection (near-wall deflection minus centerline deflection) to slab thickness is 0.28. At 15 ms, the ratio of differential deflection (near-wall deflection minus the deflection a distance t = thickness from the wall) is 0.06. The difference between these two ratios is 0.22. Typically, when evaluating modes of response (especially diagonal tension), a difference of

- < 0.15 is considered to be small.
- 0.15-0.30 is considered to be moderate.
- > 0.30 is considered to be large.

In your opinion, given this information and the deflection profiles, which category do you believe the difference of 0.22 belongs?

1. Small
2. Moderate
3. Large

Enter a value of 1-3, or just ENTER to view plot?

Figure 25. Questions in Program DEFLECT.

Combination of Early- and Late-Time Analyses

Upon completion of the program DEFLECT, the answers are transferred back to EXSYS via program RETURN for interpretation. Within EXSYS, rules 50-73 are used to linguistically interpret the answers obtained from DEFLECT. A typical example is given as rule 50 in Figure 26. In rule 50, the second antecedent deals with the early-time response of the structure. The answer to this antecedent (i.e., shear or not shear) is predetermined by the early-time analysis as explained previously. The third and fourth antecedents of the rule are determined by the external program DEFLECT. Thus, after all external programs have been run, if each of these antecedents is true, then the consequent portion of the rule is fired (i.e., late time... predominantly shear).

This example shows that, although the early-time response and the late-time response are calculated in separate external programs, the late-time response as determined by rules 50 through 73 is dependent on the combined responses. Thus, rules 50 through 73 represent all possible combinations of output from the external programs, and the late-time response is actually determined by looking at both early- and late-time responses together.

As for the overall damage, the value calculated within DEFLECT using Equation 3 is given a corresponding linguistic interpretation in rules 74-78. Rule 74 is shown in Figure 26 as an example.

Summary

In this section, the methodology used to organize a large problem in the form of an expert system was described. In particular, it was shown how rule-based information, fuzzy set theory, and calculational programs with varied functions can be implemented efficiently into a single system to help solve a complex problem. As an example, the programming techniques used to codify this information for structural integrity analysis of a buried box were described.

The output of this structural integrity module are the modes of response and levels of damage as calculated by subjective and objective information. At this point it is important to remind the reader that the output from this module is only a partial answer. This information, in turn, could be used as

RULE NUMBER: 50

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early-time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small or small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late-time response as determined by deflection profiles was predominantly shear - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 74

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and [DAMAGE LEVEL] < 0.2

THEN:

the overall damage to the structure as determined by deflection information is none - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR.

Figure 26. Example rules for the combination of early- and late-time analyses.

a priori knowledge in the modules on Functionality and Repairability, as well as being output at the end. Again, the eventual goal is a combination of analyses produced from each of the modules in order to provide an overall assessment of the damaged structure. How the information from each of the individual modules is used, is limited only by the imagination of the developer.

V. AN EXAMPLE SESSION

Having detailed the background and structure of the computer code DAPS in Sections I through IV, an example session is presented here in order to give the reader a thorough understanding of how it works. In a typical case study, the specimen used to test the prototype is usually different than those used to develop it. Because of data limitations, however, the code will be demonstrated by analyzing test element DS3.

The organization of this section is quite simple. Starting with the introduction of the code, the chronology of events from program start to program finish will be explained using figures taken from the computer monitor. The several figures presented throughout this section are actual "screen dumps" taken directly from the computer, and thus represent exactly what the user would see when sitting at the terminal.

The program is initiated by typing the words EXSYS DAPS at the DOS (disk operating system) command level. This set of commands loads the expert system shell EXSYS and all rules and external programs needed for execution. The beginning of a session with DAPS is marked by the appearance on the screen of the title/author block as shown in Figure 27. Upon pressing any key on the keyboard, an introduction to the code is presented to the user, as shown in Figure 28. The introduction provides a general background on what is to come, and also what information the user must have available in order to use the code.

The screen following the introduction (Fig. 29) contains the first question relative to the integrity of the structure. In particular, it is trying to determine if complete failure of the structure occurred. At this point, it is important to note the text at the bottom of the screen below the thin line. This text (which appears only when inside EXSYS), is a menu of possible actions that the user may take. The absence of this information at the bottom of the screen indicates that the code has exited EXSYS temporarily to an external program. Using the photographs in Appendix A as reference, the answer to the question for test DS3 is 2; complete collapse is false.

Because the answer was false, the program immediately exits EXSYS, and enters the program FUZSET. Once inside FUZSET, an explanatory screen appears as shown in Figure 30. At this point, the user is given the option of

Structural damage assessment of
reinforced concrete buried boxes
subjected to impulsive blast loadings.

by:Steve J. Savage

Press any key to start:

Figure 27. Title block screen.

The following program is an initial attempt at combining linguistic information in the form of expert opinion on damage assessement, with crisp numerical data obtained from instrumentation waveforms. This program is not an end product as such, but rather a demonstration tool of what can possibly be acheived using expert system techniques in attacking such a problem. The program makes several calls to external programs which take from a few seconds up to several minutes, so please be patient with the system.

The first portion of the code deals with the structural integrity analysis of the structure thru the use of visual information, therefore, the user will need have observed or inspected the structure, or have visual information in the form of photographic data available.

The second portion of the code deals with structural integrity analysis of the structure via numerical data. Most of the hard data has been stored internally in the form of data files, but some information must be derived from the user. Please have the following information available relating to the material, geometrical, and loading parameters of the structure : beam density, shear modulus, roof slab clear span length, slab thickness, poisson's ratio, damping coefficient, concrete compressive strength, steel yield stress, percentage steel ratio, maximum slab overpressure, load rise time, and load duration.

Press any key to start:

Figure 28. Introduction to DAPS.

```
complete failure of the structure is
     1   true (i.e:, the roof slab has been completely separated from one or
         both of its supports)
     2   false (i.e., the roof slab has not been completely separated from one
         or both of its supports)
2

------------------------------------------------------------------------------
Enter number(s) of value(s), WHY for information on the rule,
QUIT to save data entered, <ESC> for edit mode or <H> for help
```

Figure 29. Determination of failure.

```
In a moment you will be asked 10 questions pertaining to the structural
integrity of the buried box structure. These questions will deal with the
DAMAGE LEVEL of different features obtained thru visual inspection of the
damaged structure. The possible responses to these questions will be:

               1.) none
               2.) slight
               3.) moderate
               4.) severe
               5.) very extensive
               6.) unknown

For each of these linguistic terms, there is stored in a data file a
corresponding fuzzy set representation. These fuzzy sets will be used
in a fuzzy-weighted-average algorithm to determine modes of damage and
associated levels of damage in each mode. If you want to see these fuzzy
set representations (with the choice of changing them if you disagree),
simply answer yes to the following question.

         Do you want to see the fuzzy set representations
          (y = view/change, n = continue with program) ? y
```

Figure 30. Introduction to FUZZSET.

viewing/changing the fuzzy sets that will represent the linguistic damage levels described in Section IV. Having chosen yes as the response, Figure 31 appears. These two screens are used as a preview of the fuzzy sets to come. As described in the figure, these examples are given for comparative purposes only. The code then goes on to show the fuzzy sets for each of the linguistic terms: none, slight, moderate, severe, very extensive, and unknown. An example showing the screen for "moderate damage" is shown in Figure 32.

The major goal of program FUZSET is the determination of structural damage as obtained from subjective information. In order to complete this task, the program begins the interrogation of the user concerning the damage level of the ten structural attributes discussed in Section III. The introduction to that process is given in Figure 33. The remainder of program FUZSET is essentially a question and answer session, in which the user provides the necessary level of damage for each of the ten structural attributes. The standardized question format is shown in Figure 34. Note that as one of the responses, the user is allowed to view and/or change the fuzzy relations as outlined in Section IV.

If the viewer chooses 7 (view/change), he/she is greeted with Figure 35, which explains how the view/change option works. Upon choosing a damage level to view, the program retrieves the four fuzzy relationship (one for each mode) data files that the user has requested. Sample screens relating structural attribute number one to shear and flexure are shown in Figure 36. Once the user has finished viewing/changing a given set of relationships, Figure 37 appears, and the user has the option to view/change fuzzy relations at different damage levels, or to just answer the original question. In this case, the option to continue was picked, and a value of severe was chosen for structural attribute number one (Example session values: 4,3,2,3,2,3,1,5,1,2).

This process may be repeated for each of the ten attributes, or the user may simply answer the questions as they are presented. In this manner, the other nine questions were answered with appropriate responses for test DS3. Upon completion of all questions, the program FUZSET is exited, and the program COMBIN is run in order to analyze the information using the DSW algorithm. When the DSW algorithm is completed, the code returns to EXSYS where it asks the user (Fig. 38) if he/she would like to view the results obtained in COMBIN. If yes, the program COLORPLT is executed, and the calculated damage levels for each mode are displayed, e.g. see Figure 39.

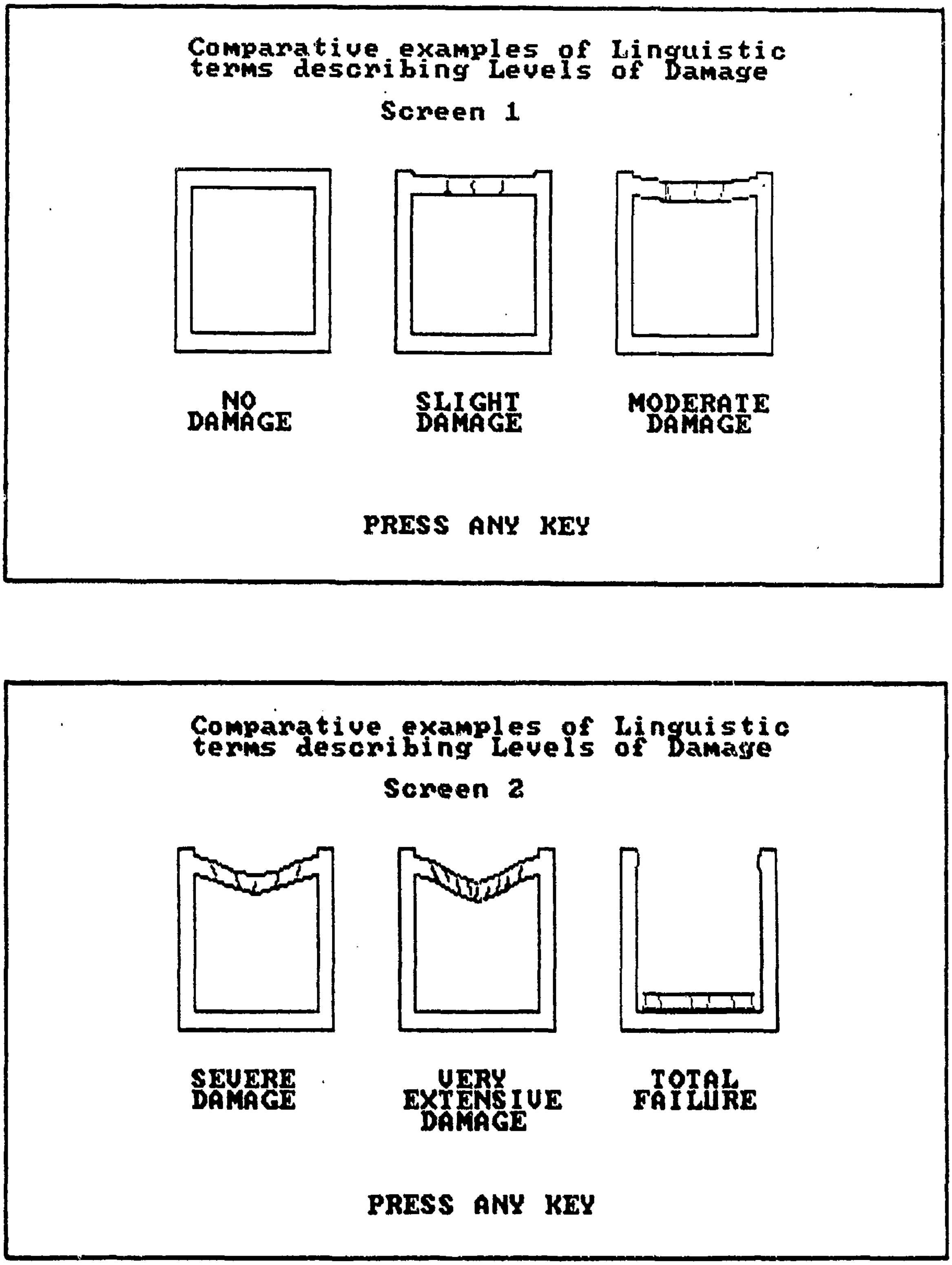


Figure 31. Graphical representation of linguistic terms.

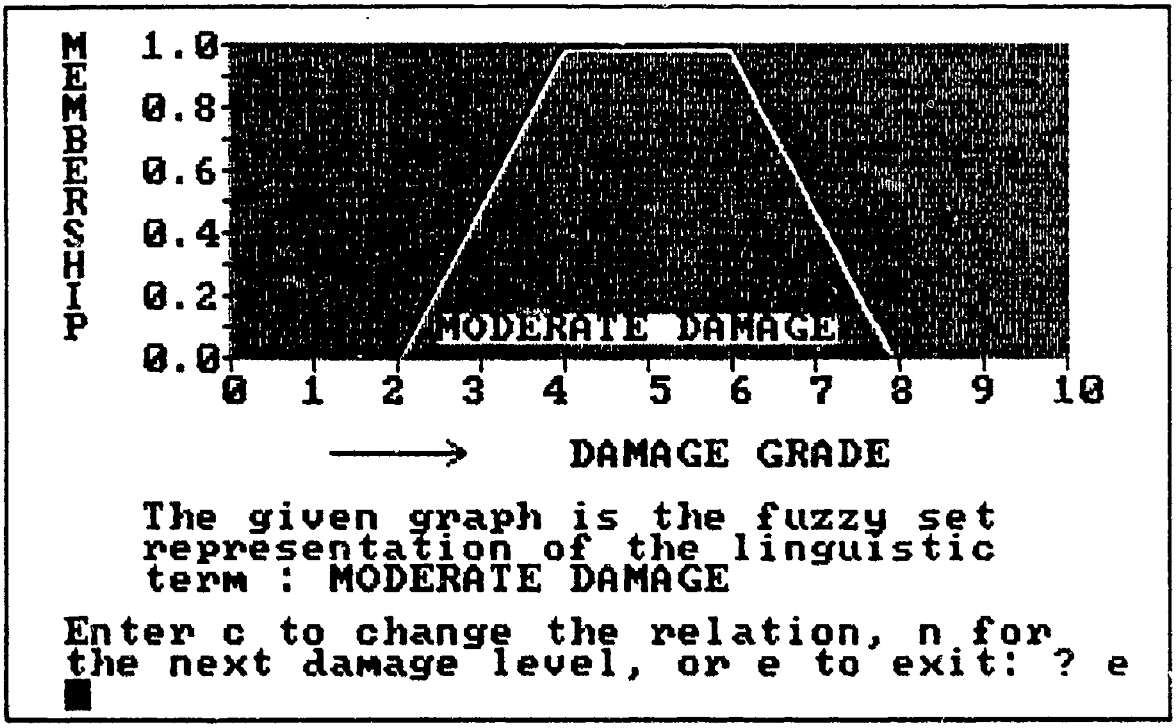


Figure 32. Fuzzy set representation of "Moderate Damage."

I am now going to ask you 10 questions concerning the level of damage of structural parameters related to structural integrity of the buried box. Your responses will be combined with expert opinion relating these same structural parameters to modes of response. This information on expert opinion is stored in data files in the form of fuzzy sets.

Press ENTER to continue ?

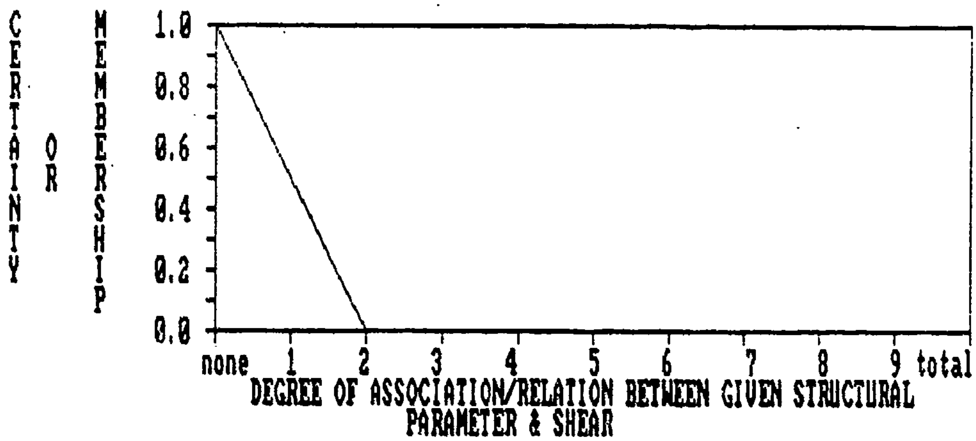
Figure 33. Introduction to subjective questions.

```
 The level or amount of  spalling and loss of concrete/rebar
interaction on the bottom side of the main slab (central 1/3
to 1/2 span) is needed.

 Depending on the amount or level of damage associated with
this parameter, a fuzzy relation (as determined by expert
opinion) between the given parameter and the different modes
of deformation will be added to a data file for later manipul-
ation. You may either choose the appropriate answer to the
question, or you may request to view and/or change the relation-
ships as outlined above, before making a decision.

                        CHOICES:
 1)  negligible
 2)  slight
 3)  moderate
 4)  severe
 5)  very extensive (concrete core in chunks. etc..)
 6)  unknown
 7)  View and/or change fuzzy relations

     Please enter the number of your choice : ? 7
```

Figure 34. Typical format of structural attribute questions.

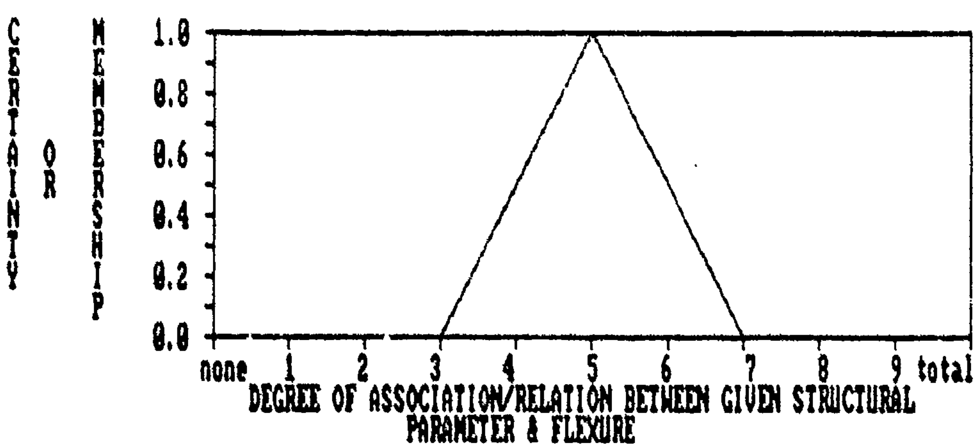
```
The current structural parameter is:  spalling and loss of concrete/rebar
            interaction on the bottom side of the main slab (central 1/3
            to 1/2 span)

The fuzzy relation between the given structural parameter and
the different modes of deformation may be different for each
level of damage. Therefore, before viewing/changing any of
these relations, you must choose a specific level of damage
to have displayed.
The choices again are: 1) None
                       2) Slight
                       3) Moderate
                       4) Severe
                       5) Very extensive
                       6) Unknown

Which damage level (vs. given structural parameter) would you like to
look at ? 3
```

Figure 35. Preview of view/change option.



GIVEN STRUCTURAL PARAMETER: spalling and loss of concrete/rebar interaction on the bottom side of the main slab (central 1/3 to 1/2 span) is: MODERATE

Enter n to view next mode relation, or c to change this fuzzy relation (NOTE: If you change this relation you will not influence similar relations for other structural parameters, damage modes, and damage levels. You only change the relation between the parameter, damage level, and damage mode shown above)?



GIVEN STRUCTURAL PARAMETER: spalling and loss of concrete/rebar interaction on the bottom side of the main slab (central 1/3 to 1/2 span) is: MODERATE

Enter n to view next mode relation, or c to change this fuzzy relation (NOTE: If you change this relation you will not influence similar relations for other structural parameters, damage modes, and damage levels. You only change the relation between the parameter, damage level, and damage mode shown above)?

Figure 36. Typical fuzzy set relation of mode versus structural attribute.

```
        You may now view/change the other fuzzy damage relations for
        the current structural parameter at a different level of damage,
        or continue the program and simply choose an appropriate
        level of damage to answer the question.

                Your choice is (v = view/change c = continue) ? c



        The level of damage of spalling and loss of concrete/rebar
     interaction on the bottom side of the main slab (central 1/3
     to 1/2 span) is :

                                  1) None
                                  2) Slight
                                  3) Moderate
                                  4) Severe
                                  5) Very extensive
                                  6) Unknown

                       Enter the number of your choice: ? 4
```

Figure 37. Exiting from the view/change option.

```
the user would like to see the results of the DSW combination process just
completed, i.e., the calculated (fuzzy set) levels of damage for each mode is
:
    1   yes - please show them
    2   no - continue program execution
1

Enter number(s) of value(s), WHY for information on the rule,
QUIT to save data entered, <ESC> for edit mode or <H> for help
```

Figure 38. Typical format of an EXSYS question.

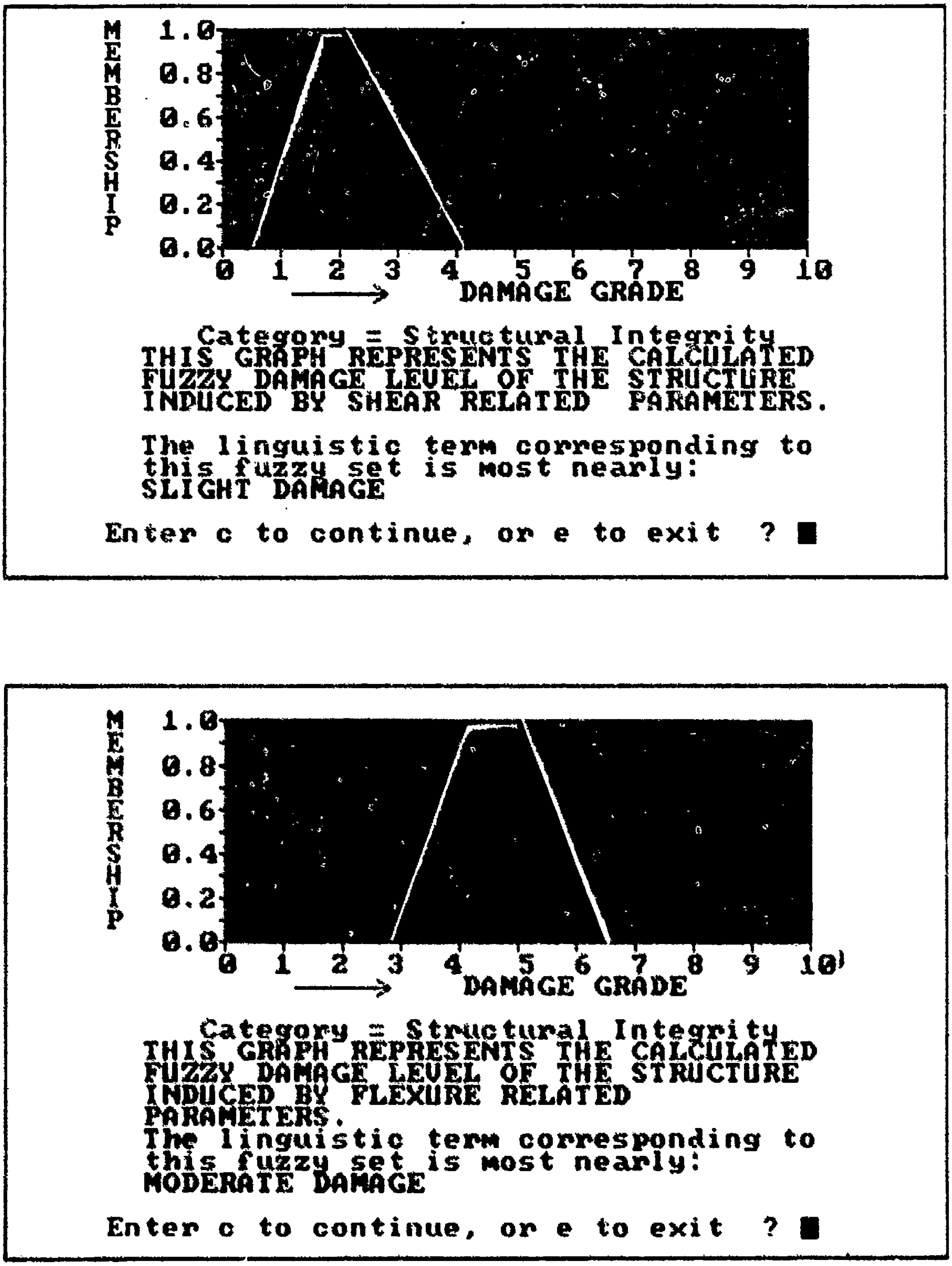


Figure 39. Results of Program COMBIN as shown by COLORPLT.

The completion of COLORPLT signals an end to the subjective information analysis, and the code returns to EXSYS. Inside EXSYS, the answers obtained in COMBIN are linguistically interpreted and presented to the user in the form of rules. In test DS3, the damage sustained in a shear mode was slight, and the overall damage to the structure is severe, as shown in Figures 40 and 41 respectively.

The next step in the analysis process is initiated when EXSYS calls the external program TIM. As discussed in Section IV, the program TIM evaluates the early-time response of the structure using a Timoshenko beam model. Input to the program is interactive and includes the material, geometrical, and loading parameters shown in Figure 42. All input for test DS3 can be found in Section II. The analysis of the data in program TIM takes approximately 2 min, after which it returns to EXSYS.

The second step in the early-time analysis is accomplished through the use of program IFPLOT. Figure 43 shows the introduction provided to the user. After viewing this introduction, the pressure/impulse versus time plots for the given structure are presented to the user as shown in Figures 44 and 45, respectively. In Figure 46, the user is questioned as to the similarity of the plots just viewed. As options, the user is allowed to look at example plots (Figs. 9 and 10) representing case 1 and case 2, or to return to the plots to study them more carefully before answering. As can be seen in Figures 44 and 45, the best answer for test DS3 is 3, i.e., no significant similarity.

Following the early-time analysis, EXSYS begins the late-time analysis by executing program DEFLECT. The introduction to this program is given in Figure 47. In Figure 48 the user is presented with the deflection profiles of the damaged structure at 3 ms and 15 ms. After viewing this plot, the user is asked three questions pertaining to the deflection profile, one of which is shown in Figure 49. Although the answers to these questions would at first seem obvious, in the event a value is borderline between two linguistic classes, the intuitive opinion of the user is quite useful.

Once DEFLECT is completed, control is returned to EXSYS. Since DEFLECT is the final external program to be executed, the only task remaining is for EXSYS to analyze the information obtained from the hard data external functions. This task, as discussed in Section IV, is accomplished through the use of several rules. As an example, Figures 50 and 51 show rules 64 and 78

```
RULE NUMBER: 14
IF:

     (1)    complete failure of the structure is false (i.e., the roof slab has
            not been completely separated from one or both of its supports)
and  (2)    shear damage is slight

THEN:

            the damage to the structure associated with shear response as
            determined by structural integrity analysis from visual
            information is slight - Probability=1

NOTE: The actual analysis procedure stated above is a fuzzy-weighted average
      algorithm implemented in a FORTRAN computer program. The damage levels of
      the 10 structural integrity parameters supplied by the user are combined
      by weighting them with expert knowledge relating modes of failure to
      these same parameters.

IF line # for derivation, <K>-known data, <C>-choices
 or  - prev. or next rule, <J>-jump, <H>-help or <ENTER> to continue:
```

Figure 40. Typical rule explaining damage related to a given mode.

```
RULE NUMBER: 40
IF:

     (1)    complete failure of the structure is false (i.e., the roof slab has
            not been completely separated from one or both of its supports)
and  (2)    overall damage is severe

THEN:

            the overall level of damage to the structure as determined by
            structural integrity analysis from visual information is severe -
            Probability=1

NOTE: The actual analysis procedure stated above is a fuzzy-weighted average
      algorithm implemented in a FORTRAN computer program. The damage levels of
      the 10 structural integrity parameters supplied by the user are combined
      by weighting them with expert knowledge relating modes of failure to
      these same parameters.                                        The overall
      damage is assumed to be the largest damage level from each of the 4 modes
      - shear, flexure, diagonal tension, tension membrane.

IF line # for derivation, <K>-known data, <C>-choices
 or  - prev. or next rule, <J>-jump, <H>-help or <ENTER> to continue:
```

Figure 41. Typical rule explaining overall damage.

```
I am now going to evaluate the early time response of the structure
using a modified Timoshenko beam analysis. Before I can do this, however,
I will need the values for the following material, geometrical, and loading
properties:

                    Beam density
                    Shear modulus
                    Slab length
                    Slab thickness
                    Shear deformation coefficient
                    Poisson ratio
                    Damping coefficient
                    Concrete compresssive strength
                    Steel yield stress
                    Reinforcing ratio
                    Maximum slab overpressure
                    Load rise time
                    Load duration time

What is the value of the beam density [lb s**2 / in**4]
.000225
Is this value correct (y or n) ?
y
```

Figure 42. Introduction to Program TIM.

```
     In a moment you will be shown a pressure vs. time plot
and an impulse vs. time plot of a test specified by you.
The interface pressure and corresponding impulse at the
center line, near the support, and over the support will be
superimposed on each other.  The purpose of this is to
determine the similarity of the response at different
locations.  The similarity of pressure/impulse at different
locations is helpful in determining the initial response
mode.

     After viewing the pressure vs. time plot and the
impulse vs. time plots you will be asked a question
pertaining to the above mentioned similarity.  You may either
answer the question promptly, or view the plots again in
order to study them more carefully before producing an
answer.

                  STRIKE ANY KEY TO CONTINUE
```

Figure 43. Introduction to Program IFPLOT.

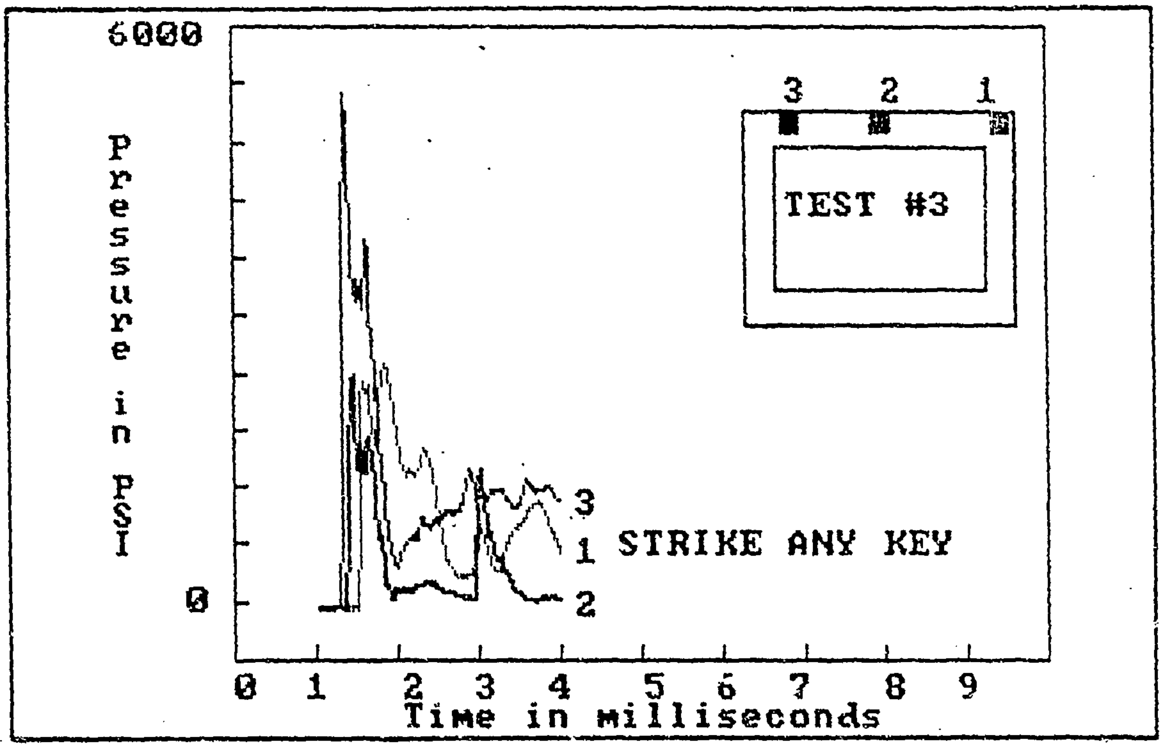


Figure 44. Interface pressure versus time at three locations.

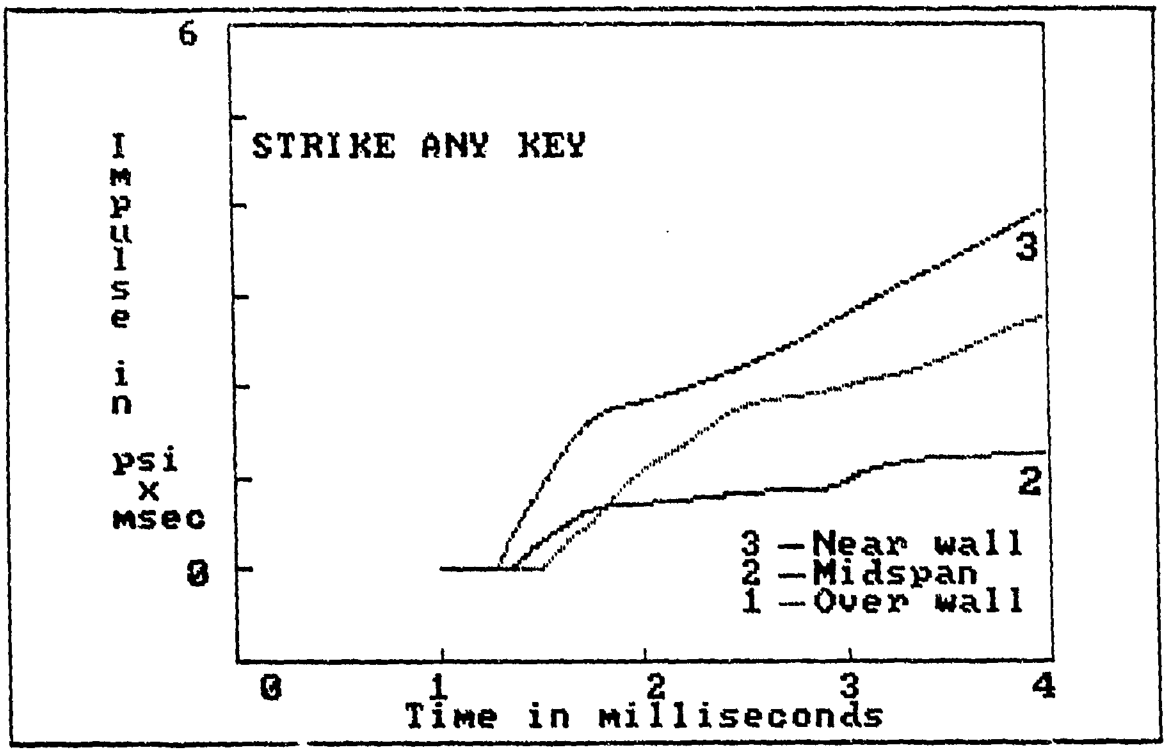


Figure 45. Impulse versus time plots at three locations.

```
                              QUESTION:
In your opinion, which of the cases below best describes the given plots ?

  Case 1  -  Pressure/impulse plots at: location 1 closely resembles
             location 3, AND location 2 is significantly different
             than both 1 and 3.

  Case 2  -  Pressure/impulse plots at: location 2 closely resembles
             location 3, AND location 1 is significantly different
             than both 2 and 3.

  Case 3  -  The plots suggest that the similarity of pressure/impulse
             is somewhat between conditions 1 and 2 above (i.e., no
             significant similarity exists as stated above).


             NOTE:  As this is a very subjective question, you may
             view two example plots that in the authors opinion,
             represent cases 1 and 2.  This may aid you in making your
             decision.  If you would like to view these examples
             choose 'e' below.

   YOUR CHOICE (1,2,3, e for example, or c to view the plots again): 3
```

Figure 46. IFPLOT question concerning interface pressure plot similarity.

```
In a moment, you will be shown the deflection profiles of the
underside of the roof slab at 3 and 15 msec after initial loading.
You will be asked for the particular test number you're assessing.
Along with the deflection profiles, you will be asked a few
questions pertaining to this plot. As you answer the questions,
you may want to view the deflection profiles first; therefore,
you may use the ENTER key to toggle back and forth between the
questions and the plot.


                      Press ENTER to continue?
```

Figure 47. Introduction to Program DEFLECT.

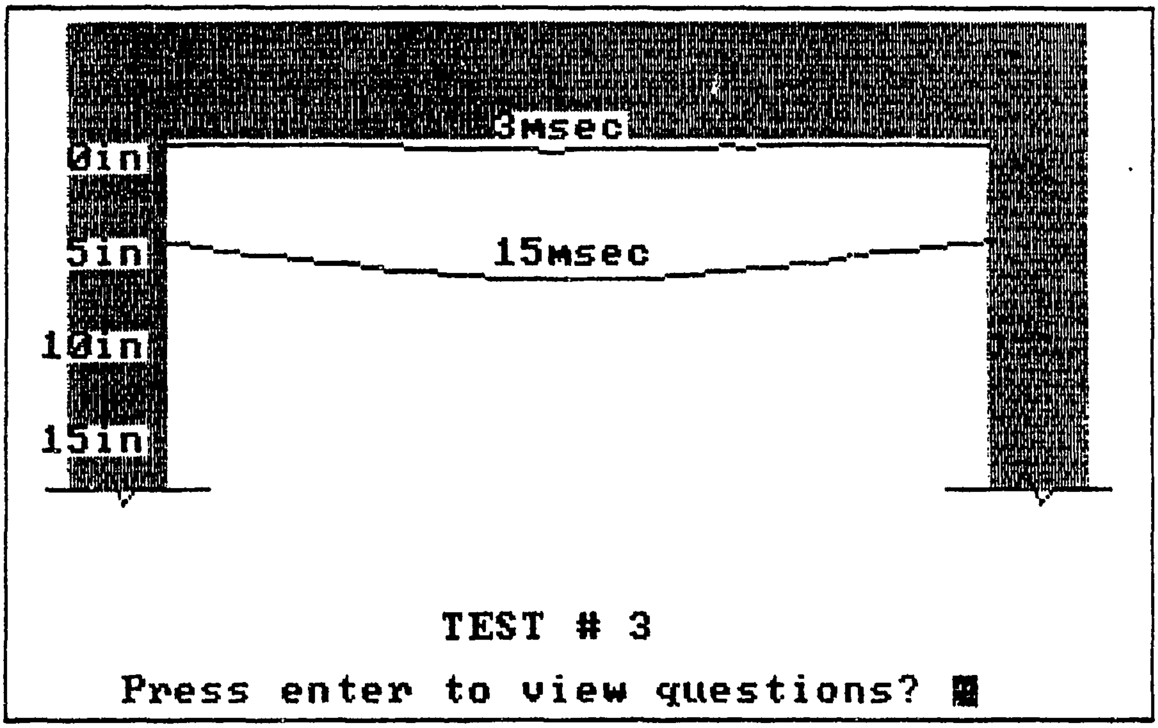


Figure 48. Typical deflection profiles at 3 and 15 ms.

At 15 msec, the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness is .28 . Typically, when evaluating modes of response (especially flexure and tension membrane), a ratio in the range of:

≈ < 0.3 is considered relatively flat
≈ 0.3 - 0.6 is considered moderately curved
≈ > 0.6 is considered highly curved

In your opinion, given this information and the deflection profile, which category do you think the given ratio of .28 belongs :

1.) Relatively flat
2.) Moderately curved
3.) Highly curved

Enter a value of 1-3, or just ENTER to view plot ? 1

Figure 49. Question 2 in Program DEFLECT.

```
RULE NUMBER: 64
IF:

      (1)     complete failure of the structure is false (i.e., the roof slab has
              not been completely separated from one or both of its supports)
and   (2)     early time response as determined by a combination of Timoshenko
              beam analysis and interface pressure data falls into the vague area
              of flexure-shear = 1
and   (3)     the near wall deflection as determined by the external program
              DEFLECT.BAS is moderate or large
and   (4)     the ratio of differential deflection (near wall deflection minus
              centerline deflection) to slab thickness implies a relatively flat
              surface

THEN:

              late time response as determined by deflection profiles was
              predominantly shear (even though early response did not show
              overwhelming evidence to this) with some residual flexure  -
              Probability=1
 and          [LATE RESPONSE] IS GIVEN THE VALUE 1

------------------------------------------------------------------------------
IF line # for derivation, <K>-known data, <C>-choices
 or  - prev. or next rule, <J>-jump, <H>-help or <ENTER> to continue:
```

Figure 50. Typical rule interpreting late-time response.

```
RULE NUMBER: 78
IF:

      (1)     complete failure of the structure is false (i.e., the roof slab has
              not been completely separated from one or both of its supports)
and   (2)     [DAMAGE LEVEL] > 1.0

THEN:

              the overall damage to the structure as determined by deflection
              information is very extensive - Probability=1

NOTE: the value of the variable [DAMAGE LEVEL] is determined in the external
      program DEFLECT.FOR and returned via the program RETURN.FOR. The value of
      the variable is computed as the integral of the deflection (over the
      length of the slab) at 15 msec. divided by length times thickness (to
      produce a dimensionless parameter).

------------------------------------------------------------------------------
IF line # for derivation, <K>-known data, <C>-choices
 or  - prev. or next rule, <J>-jump, <H>-help or <ENTER> to continue:
```

Figure 51. Typical rule interpreting overall damage to the structure as determined by the hard data.

which describe the modes of response and overall damage of the structure, respectively. Finally, all important information derived throughout the session is given as output at the end of the run as shown in Figure 52. At this point, the user may either end the session or use the menu at the bottom of the page to explore the answers. By using the facilities within EXSYS, the user is able to back-chain through the rules in order to see how a particular piece of information was derived.

```
          Values based on 0/1 system                                 VALUE

1    the external program FUZSET.BAS has been run                        1
2    the external program COMBIN.FOR has been run                        1
3    the external program PLOT.BAS has been run                          1
4    the damage to the structure associated with shear response as
     determined by structural integrity analysis from visual
     information is slight                                               1
5    the damage to the structure associated with diagonal tension
     response as determined by structural integrity analysis from
     visual information is slight                                        1
6    the damage to the structure associated with a flexure response
     as determined by structural integrity analysis from visual
     information is moderate                                             1
7    the damage to the structure associated with tensile membrane
     response as determined by structural integrity analysis from
     visual information is severe                                        1
8    the overall level of damage to the structure as determined by
     structural integrity analysis from visual information is
     severe                                                              1
9    the external program TIM.FOR has been run                           1
10   the external program IFPLOT.BAS has been run                        1
---------------------------------------------------------------------------

Press any key for more:
```

```
          Values based on 0/1 system                                 VALUE

11   early time response as determined by a combination of
     Timoshenko beam analysis and interface pressure data falls
     into the vague area of flexure-shear                                1
12   the external program DEFLECT.BAS has been run                       1
13   late time response as determined by deflection profiles was
     predominantly shear (even though early response did not show
     overwhelming evidence to this) with some residual flexure           1
14   the overall damage to the structure as determined by
     deflection information is very extensive                            1

---------------------------------------------------------------------------
All choices <A>, only if value>1 <G>, Print <P>, Change and rerun <C>,
rules used <line number>, Quit/save <Q>, Help <H>, Done <D>:
```

Figure 52. Output of DAPS for Test DS3.

VI. REVIEW, CONCLUSIONS, AND RECOMMENDATIONS

REVIEW

Structural damage assessment of buried protective structures is a very complex subject which is imbued with a large amount of uncertainty and vagueness. This is due to the fact that much of the information used in the analysis process is derived from expert opinion and uncertain numerical data. Because of this, a new approach for combining this type of information was studied. Of particular interest was the feasibility of incorporating both soft data in the form of expert opinion and hard data produced from instrumentation waveforms into a structural damage assessment code.

The data base used in this study is derived from a series of experimental tests conducted in 1981 and 1982 on eleven buried reinforced concrete boxes. The boxes were subjected to extremely high impulsive blast pressures and thus sustained levels of damage ranging between slight degradation and complete collapse. Major modes of response observed in the test structures included direct shear at the supports, flexure of the main slab, and tension membrane at both supports and midspan induced by large deflections. Evidence of all these modes of response were obtained from experimental data comprised of interface pressure data, strain data, and deflection information obtained from high- speed photography.

The framework developed in this report is incorporated in a rule-based expert system approach. In an expert system scheme, difficult problems are subdivided into smaller problems, which in turn are represented in antecedent-consequent pairs as rules. These rules are combined with other data and information to form what is called the knowledge base. The processing and analysis of this information is controlled through an inference mechanism, which retrieves necessary information from the user or the knowledge base using either backward or forward chaining.

In this study, an analysis of structural integrity of the buried box element was accomplished using the expert system shell EXSYS as the control mechanism to combine subjective and objective information and as a mechanism to chain through the rule base. Expert opinion on damage assessment obtained from questionnaires was used as the basis for the subjective portion of the

code. Because this type of information is vague and uncertain, fuzzy set theory was used to quantify linguistic variables. Also, because of the size and complexity of the problem, a numerical method in the form of a fuzzy-weighted-average algorithm was used instead of rules to synthesize the subjective information.

Objective data, on the other hand, was obtained through the use of external programs which "reach out" and "hook" numerical information from digitized waveforms. This information is then passed back to the rule-based inference module where it is analyzed or interpreted through the use of rules.

CONCLUSIONS

The basic purpose of this report was to study the feasibility of using an expert system approach in the area of survivability and vulnerability analysis of buried protective structures. As such, several interesting conclusions may be drawn from this work.

First, the assessment of damage to protective facilities is a highly complex problem requiring innovative analysis techniques for three reasons. One, due to the extreme nature of the short-lived transient loading condition, many factors affect the dynamic response of the structure. These factors include loading parameters such as peak pressure and rise time, material properties like concrete strength and soil type, and geometrical properties like length-to-depth ratio, end restraint, and depth of soil overburden. Because of the interaction of these various parameters, modes of response which are unique to this problem (direct shear for example) can be induced in the structure. Two, damage assessment is a fundamentally subjective concept and thus requires the use of linguistic interpretation and engineering judgment to analyze the problem. This adds to the complexity of the situation because both linguistic information and engineering judgment are inherently difficult to quantify. Three, an overall assessment of the structure cannot rely on structural integrity analysis alone but must also include the concepts of functionality and repairability for completeness. Analysis is complicated further when it is also realized that each of these concepts may be interrelated.

Second, although the information obtained from expert opinion can be quite useful, the decomposition of this information is no trivial task.

Problems encountered include; interpreting linguistic terms; uncertainty in expert opinion; deciphering different terminology used to describe the same concept; and subdividing and organizing the information into a meaningful structure. Also, if the problem (to which the information will be applied) is sufficiently complex, difficulties such as the combinatorial explosion described in Section IV may arise. In this particular case, the problem was circumvented through the use of a fuzzy-weighted-average algorithm, rather than the conventional rule-based format.

Third, although the term "objective data" was used in this work to describe numerical information obtained from instrumentation waveforms, it was found that these data do contain some inherent subjectivity. The subjectivity arises when we try to use discrete numerical quantities derived from continuous functions. For example, discrete values of deflection are used in Section IV to describe various modes of damage. Deflection of the roof slab at any given point, however, is a function of both time and position. Therefore, the choice of a discrete deflection value is a subjective decision. The approach used in this report was to use engineering judgment to classify the various numerical quantities into different linguistic levels, then proceed with the analysis using these linguistic values.

Fourth, a careful analysis of the problem and a review of the literature reveals that typical analytical methods (deflection ratios, dissipated hysteretic energy, etc.) employed in describing levels of damage, have limited use in the case under study. Calculation of different damage measures revealed that, at the present time, not enough is known about late-time effects on structural response produced by changes in loading, material, and geometrical parameters. For example, a simple damage measure using energy and impulse was calculated at two points along the roof span. Although the measure predicted damage well within a group containing similar geometrical and material parameters, it was not able to predict damage when these parameters were changed. Therefore, without an understanding of parameter effects on response, developing a good measure of structural damage is difficult.

Fifth, the theory of fuzzy sets can be quite effective in interpreting linguistic information that is either vague, imprecise, or uncertain. The assignment of fuzzy sets to linguistic terms and the combination of these quantities is a straightforward procedure. The major difficulty in

confronting this situation is that of providing linguistic terms for calculated fuzzy sets. Equation 6 was used in this study to provide a relative measure of similarity between sets. In the event that a calculated fuzzy set falls between two predefined fuzzy sets, the equation simply assigns the linguistic term corresponding to the more similar of the two. In practice, however, a better approach would be to assign a linguistic term which is a compromise of the two. Thus, although Equation 6 is adequate for demonstration purposes, other techniques could be developed which would better interpret results obtained from fuzzy operations.

Sixth, although quite useful for some parts of a problem, a rule-based format is not feasible in certain cases where the interrelationship of a large number of variables makes the problem too complex. Such a problem was described in Section IV concerning the experts' opinion. However, the use of expert system techniques allows the integration of such situations into the problem. In this case, the problem was circumvented through the use of an external program which manipulated and combined the data. Similarly, other types of strategies can be employed in the solution of a problem. Besides those discussed in this report, other tools such as finite element codes or pattern recognition techniques (Refs. 8,9) could also be used.

RECOMMENDATIONS

Based on the information learned from this study, the following recommendations are presented for possible future work.

1. Because of time constraints, it was not possible to test the code on structures other than those in the WES dynamic test series. Therefore, the code should be tested against another test series in order to determine its strengths and weaknesses.

2. As was shown in Figure 17, the work undertaken in this report comprises only the structural integrity module. In order to complete the code, modules on functionality and repairability should also be developed.

3. The only objective data used in this study included interface pressures and deflection profiles. As discussed in Section III, other objective data are available and should be studied for possible inclusion into the hard data section in order to make it more complete. The possibility of using pattern recognition procedures on the data should be explored.

4. The expert matrix [E] described in Section IV was developed using the authors' opinions as its basis. A final version of the matrix, however, should be composed of the opinions of several experts. The information used to fill this matrix was collected through the use of a second questionnaire sent to seven experts, but time constraints did not permit its inclusion in this report. Therefore, analysis of the information and integration into the code should be accomplished.

5. A detailed parametric study should be conducted to determine the effects of different parameters (load intensity, concrete strength, length-to-depth ratio, and reinforcing ratio) on the late-time response of the structure. An early-time analysis capability currently exits in DAPS. With the incorporation of a late-time analysis to complement the existing early-time analysis, a study of suitable damage level measures can be undertaken.

6. More work needs to be done in the area of similarity and difference measures. Specifically, better techniques are needed for converting calculated fuzzy sets into meaningful linguistic interpretations.

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APPENDIX A

PHOTOGRAPHS OF DAMAGED STRUCTURES

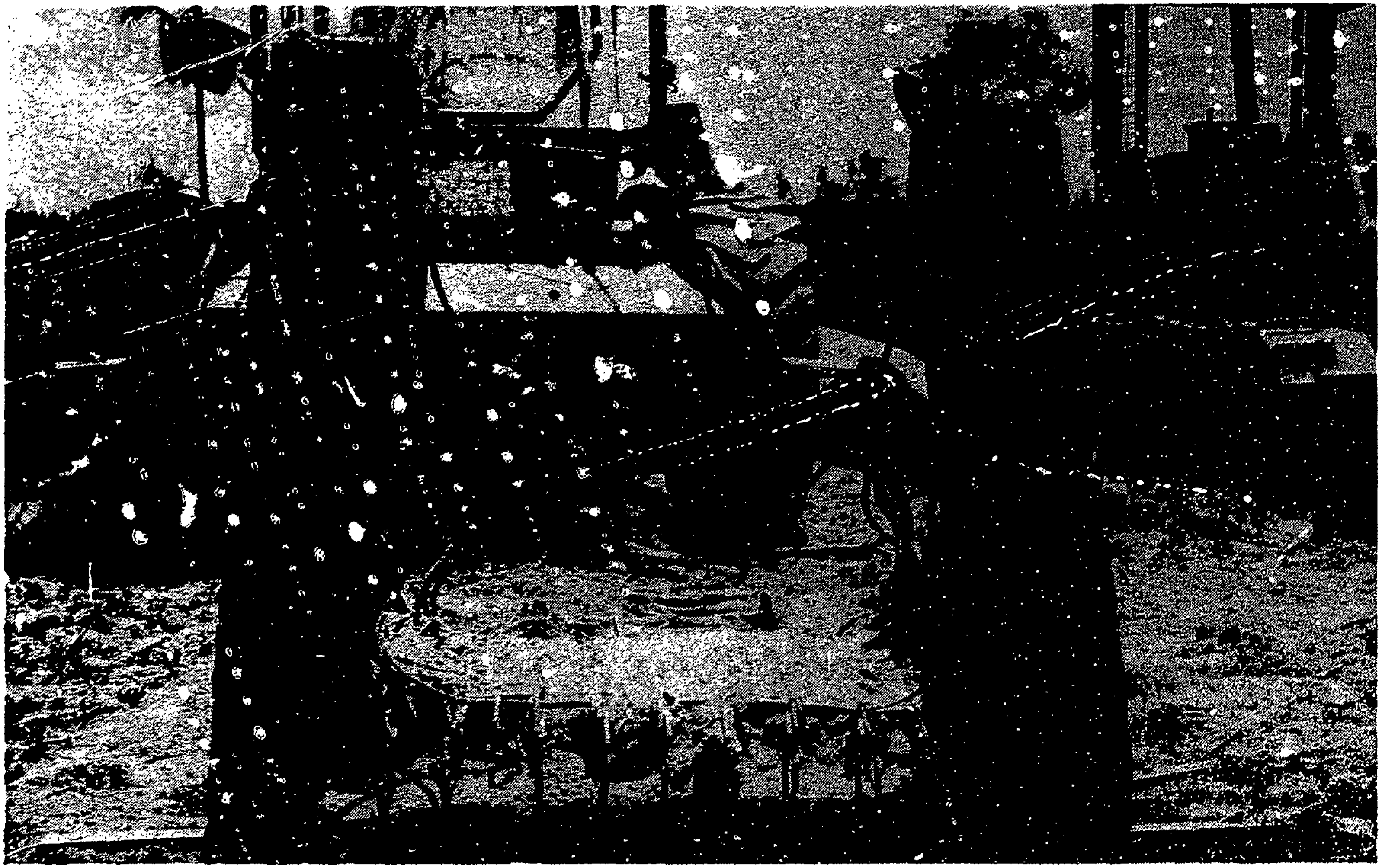

Figure A-1. Posttest photograph of Test Element DS1.

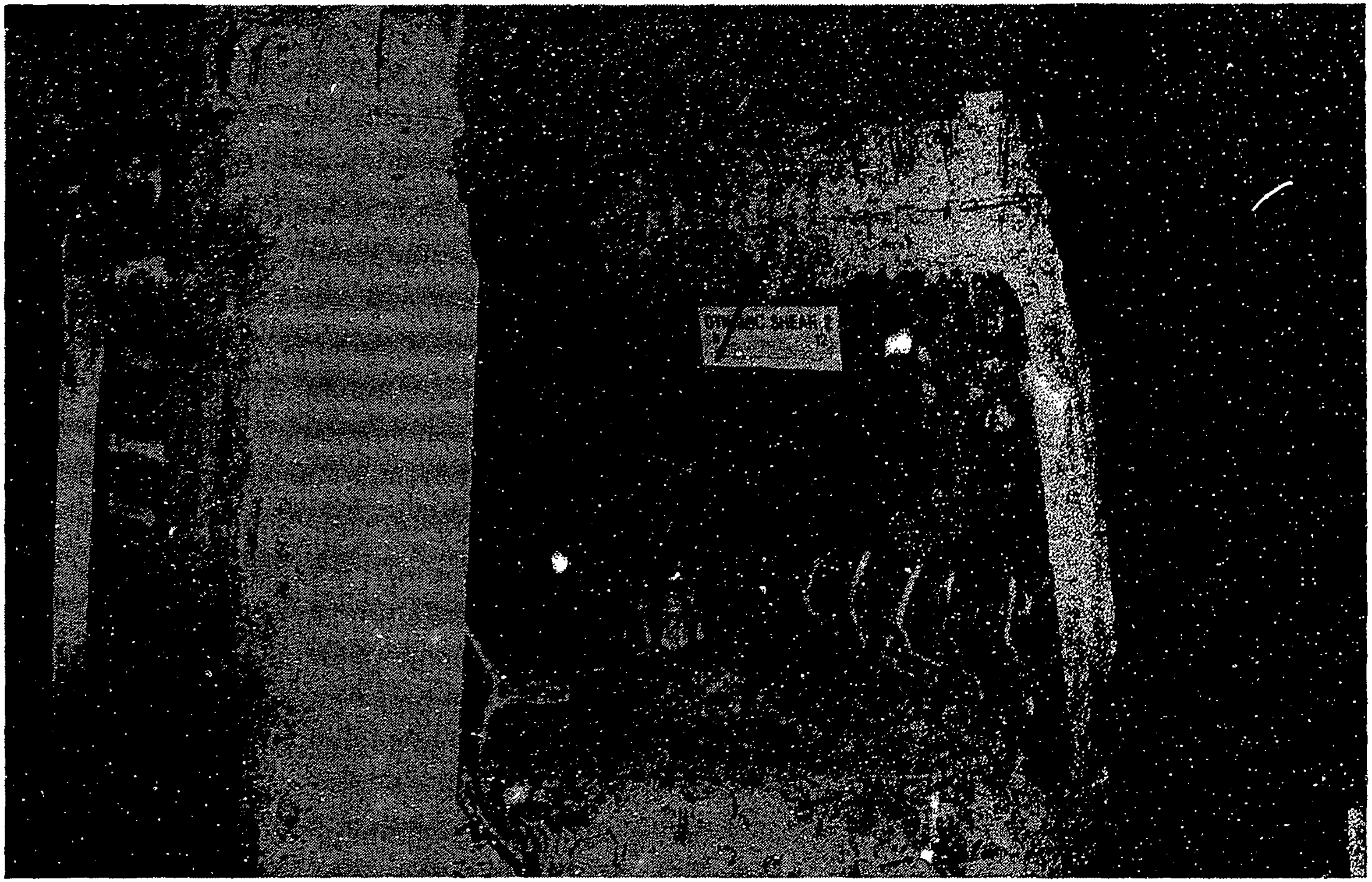

Figure A-2. Posttest photograph of Test Element DS2.

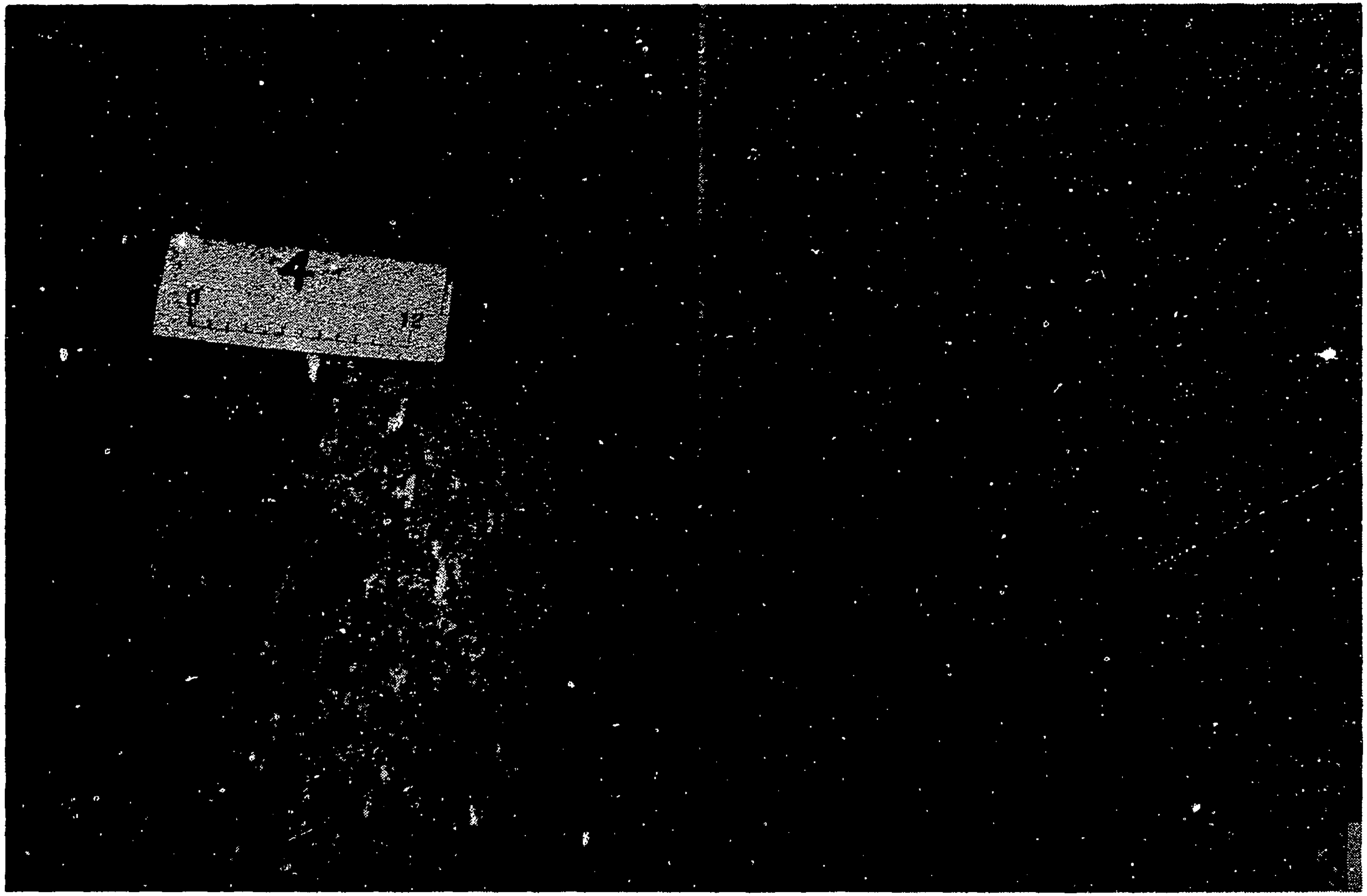

Figure A-3. Posttest photograph of Test Element DS3.

Figure A-4. Posttest photograph of Test Element DS4.

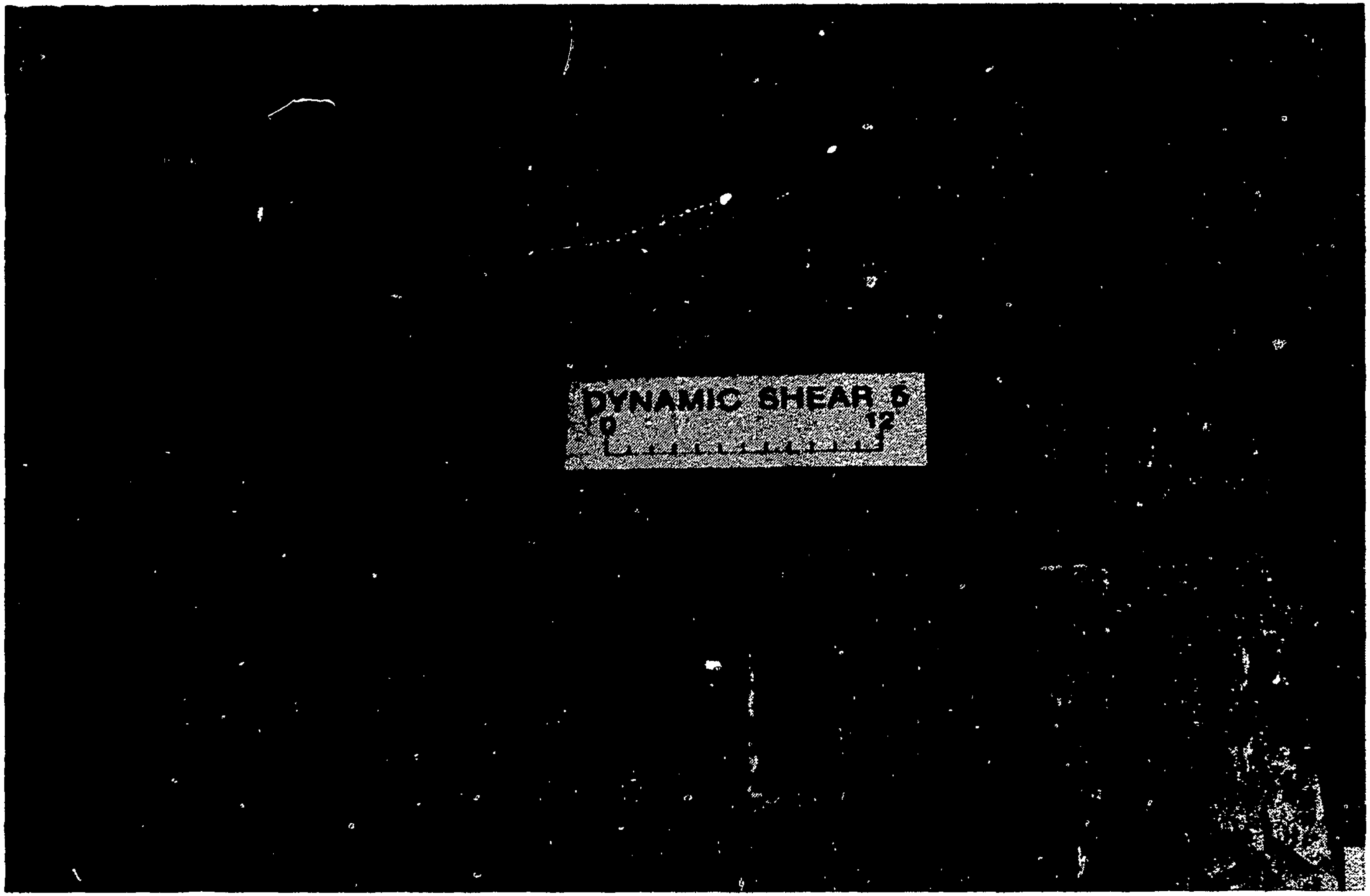

Figure A-5. Posttest photograph of Test Element DS5.

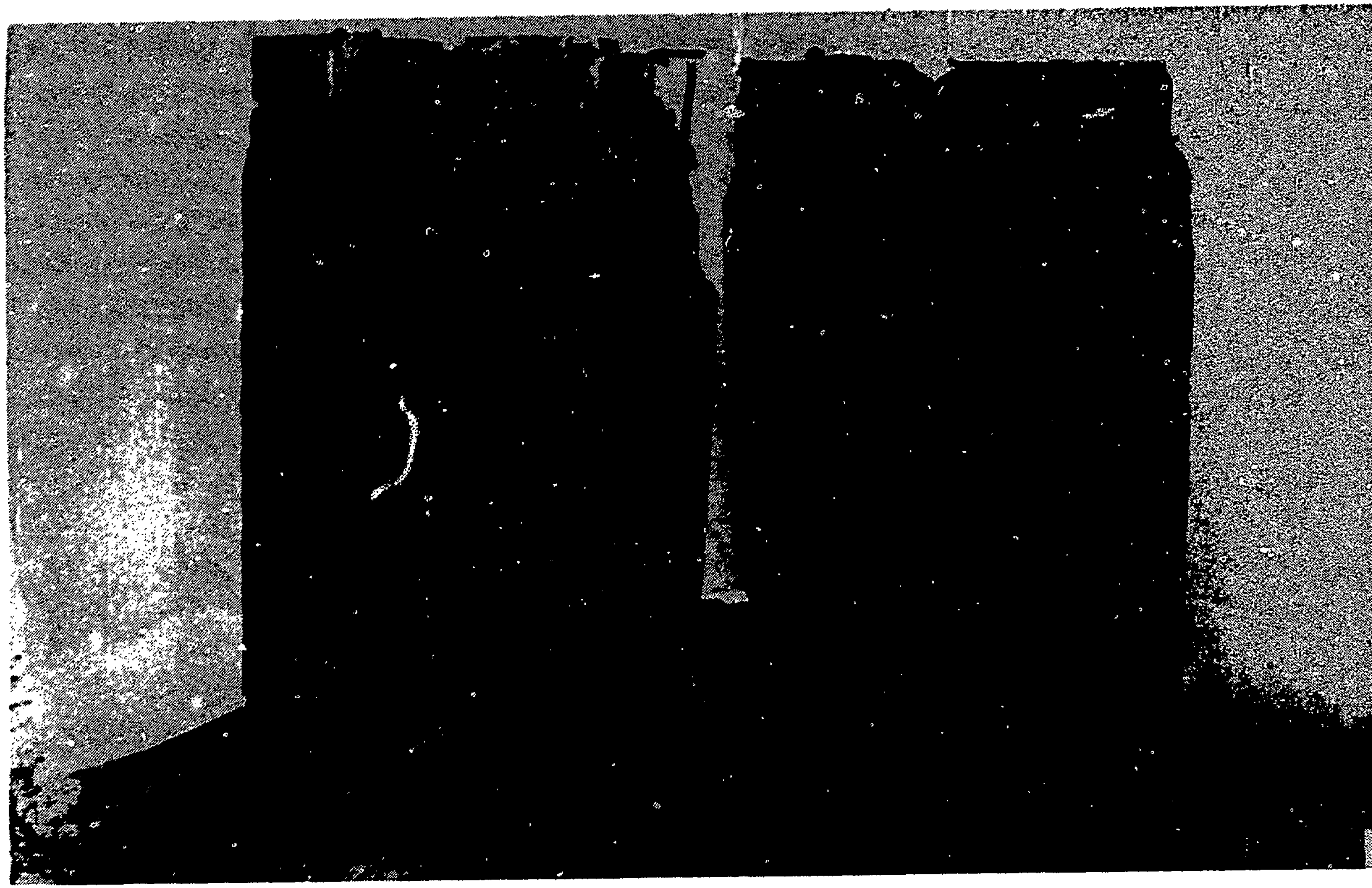

Figure A-6. Posttest photograph of Test Element DS5.

Figure A-7. Posttest photograph of Test Element DS2-1.

Figure A-8. Posttest photograph of Test Element DS2-2.

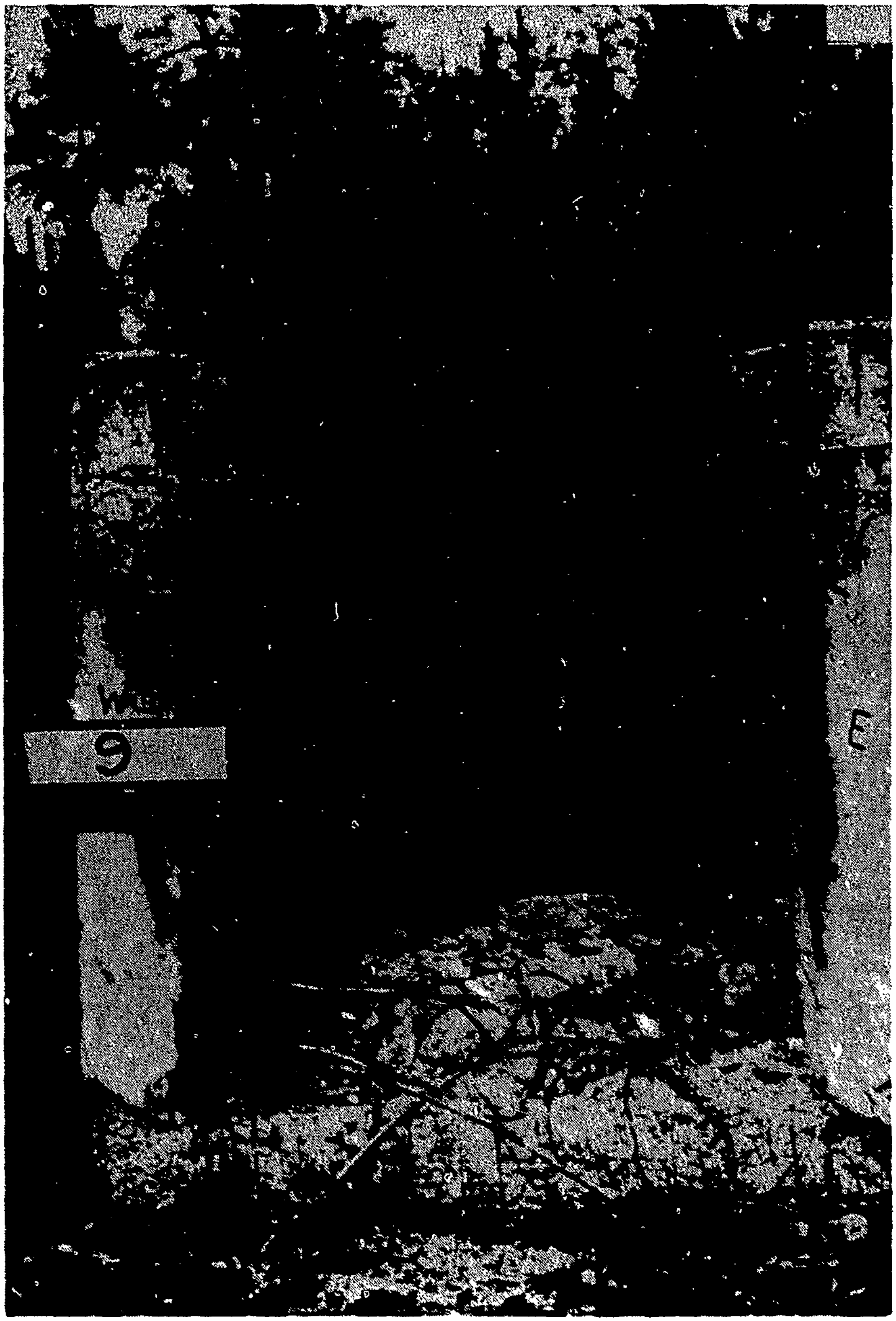

Figure A-9. Posttest photograph of Test Element DS2-2

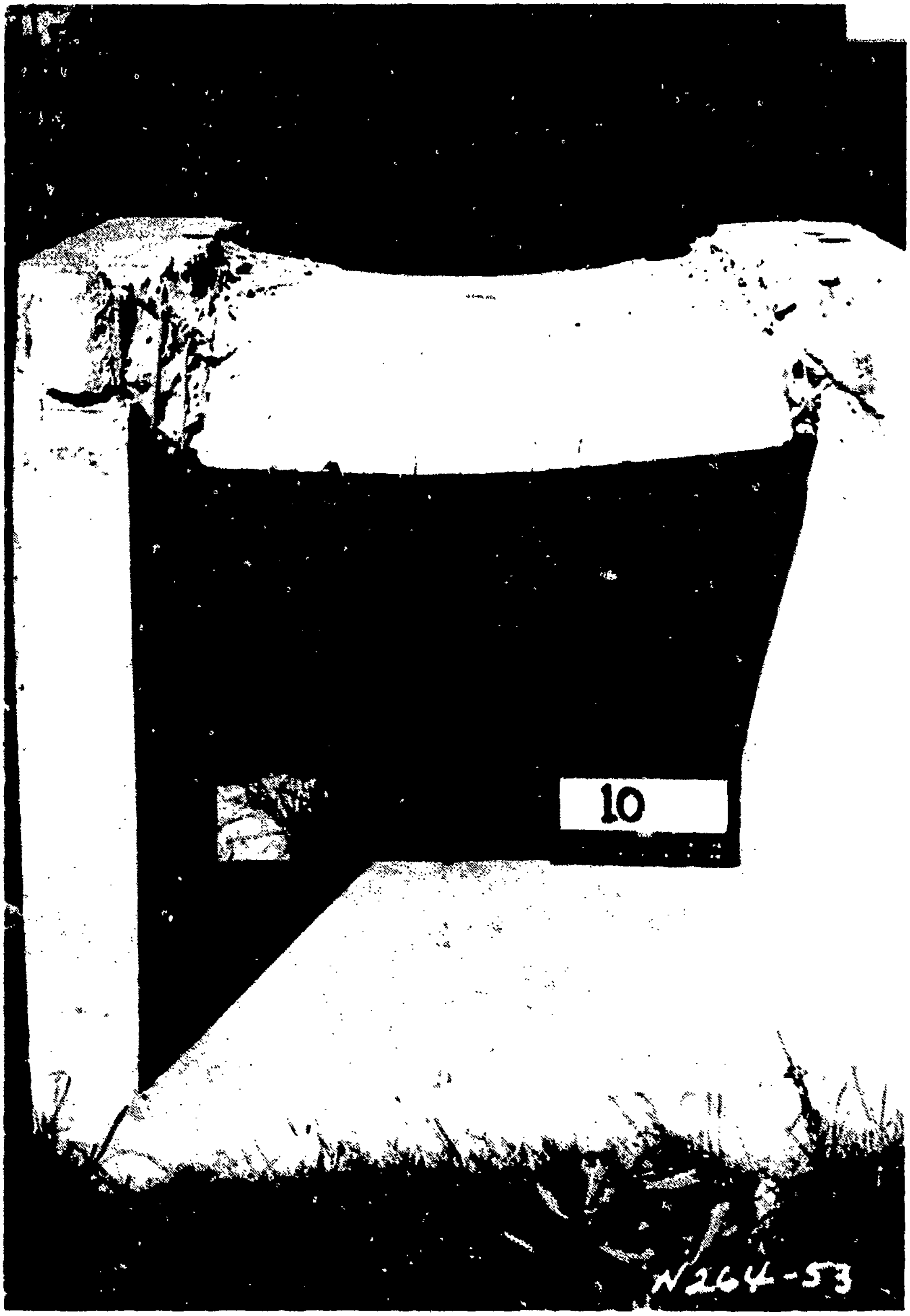

Figure A-10. Posttest photograph of Test Element DS2-3.

Figure A-11. Posttest photograph of Test Element DS2-4.

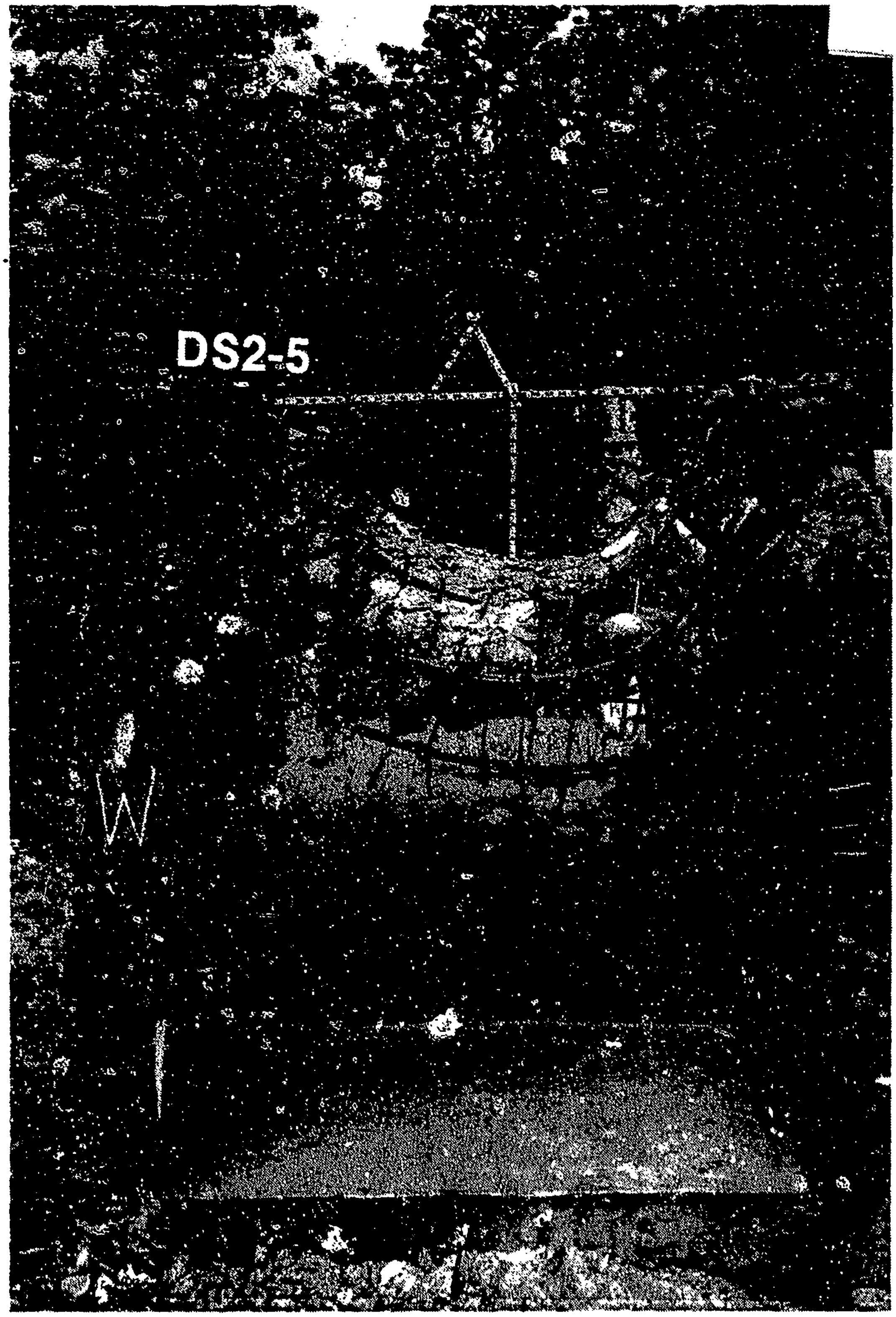

Figure A-12. Posttest photograph of Test Element DS2-5.

Figure A-13. Posttest photograph of Test Element DS2-6.

APPENDIX B

EXPLANATION OF EXSYS FEATURES

EXSYS is a generalized expert system development package. The package runs on IBM PC or compatible-type computers with 256K RAM or greater. EXSYS can create about 700 rules, with an average of 6 or 7 conditions, per 64K of memory over 192K. This is roughly 5000 rules in a PC with 640K RAM. Some of the more important features of EXSYS are detailed here.

<u>EDITOR</u>

Expert systems are generated in EXSYS using a rule editor program called EDITXS. This editor enables you to easily edit rules along with providing a simple and rapid way of putting rules into the computer and testing the rules as they are generated. Rules are input into the knowledge base through the use of several menus and templates. All linguistic input is in the form of normal human language, and thus no computer languages or special procedures need be learned before using it. This feature makes the use of expert system shells very appealing to both novices and experienced computer programmers.

* The format of a rule entered into EXSYS is as follows:

```
     IF:
             Conditions
    THEN:
             Conditions
     and     Choices
    ELSE:
             Conditions
     and     Choices

    NOTE: --------------------------
    REFERENCES: ----------------------
```

"Condition" - A condition is simply a statement of fact. In EXSYS, there are two main types of conditions: text and mathematical. A text condition is a sent... that may be true or false. The condition is made up of two parts, a

Qualifier and one or more Values. The Qualifier is usually the part of the condition up to and including the verb. The Values are the possible completions of the sentence started by the Qualifier.

"Choices" - Choices are all the possible solutions to the problem among which the expert system will decide. The goal of EXSYS is to select the most likely choice based on input data or to provide a list of possible choices arranged in order of likelihood.

CALCULATIONAL SYSTEMS

EXSYS has three built in calculational systems for handling uncertainty in Qualifier and Choice decisions.

0 or 1 system - this system should be used when the choice or qualifier is perfectly true or perfectly false. There is no ranking of acceptable choices in this system, it is a simple yes or no situation.

0 - 10 system - this is the most generally useful system, especially if probabilistic rules are used (e.g., if a condition is true, there is an 80% likelihood that choice X is appropriate). Values of 0 and 10 allow you to completely eliminate (0) or definitely include (10) a choice. The remaining values of 1-9 are averaged over the rules used.

-100 to +100 - this system is similar to the 0-10 system, except it allows data to be combined as independent or dependent probabilities. If the rule base is such that precise statistical data are available, then use this system.

MATHEMATICAL EXPRESSIONS AND VARIABLES

While many expert systems can be developed without the use of numeric variables, the ability to calculate numeric variables is a powerful tool. Even if mathematical calculations are not needed in the expert system, numeric variables can be used to flag text for display at the end of a run. Mathematical expressions containing variables can be used to derive information in the IF and THEN portions of the rule just like any other qualifier. Variables may be either string or numeric. Mathematical

expressions involving numeric variables can be combined using the basic algebraic operations (+,-,/,*), trigonometric operations, exponentiation, and others.

EXTERNAL PROGRAMS

External programs can be called from within EXSYS for data acquisition and calculation, and then can be passed back to EXSYS for analysis. EXSYS can directly receive data from automatic testing equipment, data bases, spread sheets, and dedicated programs. The process involved in calling external programs to get the value for a specific qualifiers or numeric variables is quite simple. Each qualifier or variable has an explanatory test associated with it. In order to run an external program, it is necessary only to start the text associated with the qualifier/variable with:

RUN(filename)

where "filename" is the name of the external program to run. Data are passed to external programs via the file PASS.DAT and returned via the file RETURN.DAT. Therefore, the program must only be able to read and write to these disk files.

INFERENCE MECHANISM

The different types of inference mechanisms (forward and backward chaining) were described in Section IV. A newly added feature of EXSYS that makes it very powerful is the ability to use either forward or backward chaining or combinations of both. The choice of inferencing schemes is chosen before running the expert system as part of the command line options.

EXPLANATION FEATURES

At the end of an EXSYS run, or when a rule is displayed, or information is asked of the user, the user has the option of asking the computer one of several things:

1. The computer may display the rule or rules that allowed it to derive the information. A rule used for derivation will have information about the condition the user is asking for in its THEN part. The user may then continue asking how the computer knew that the rule's IF conditions were true and so

on. If asked about a condition that is an algebraic expression, the values of the variables in the expression will be displayed. The user may then ask how these values were derived by entering the number of the variable.

2. The computer may respond that you told it the information was true.

3. The computer may respond that it does not yet know if the condition is true.

4. If the information came from an external program, EXSYS will give the program name from which it came.

The features outlined here are but a few of the capabilities of EXSYS. For further information, see the owner's manual, or contact EXSYS at: EXSYS, Inc., P.O. Box 75158, Contr. Sta. 14, Albuquerque, NM 87194, (505) 836-6676.

APPENDIX C

RULES

Subject: Structural damage assessment of reinforced concrete buried boxes subjected to impulsive blast loadings.

Author: Steve J. Savage

Starting text:

The following program is an initial attempt at combining linguistic information in the form of expert opinion on damage assessment with crisp numerical data obtained from instrumentation waveforms. This program is not an end product as such, but rather a demonstration tool of what can possibly be achieved using expert system techniques in attacking such a problem. The program makes several calls to external programs which take from a few seconds up to several minutes, so please be patient with the system.

The first portion of the code deals with the structural integrity analysis of the structure through the use of visual information; therefore, the user will need to have observed or inspected the structure or have visual information in the form of photographic data available.

The second portion of the code deals with structural integrity analysis of the structure via numerical data. Most of the hard data have been stored internally in the form of data files, but some information must be derived from the user. Please have the following information available relating to the material, geometrical, and loading parameters of the structure : beam density, shear modulus, roof slab clear span length, slab thickness, Poisson's ratio, damping coefficient, concrete compressive strength, steel yield stress, percentage steel ratio, maximum slab overpressure, load rise time, and load duration.

Ending text:

The information to follow is the output from the program DAPS. At the present time, the only information to be output is the damage level to the structure and most likely modes of deformation as determined by: 1) structural integrity analysis via soft data , and 2) structural integrity analysis via hard data. All applicable rules are used in data derivations.

RULES:

RULE NUMBER: 1

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)

THEN:
[FAILURE MODES] IS GIVEN THE VALUE "NOT KNOWN"

RULE NUMBER: 2

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)
and the failure has occurred at the slab-wall connection
and the separated slab is lying flat on the floor (implying a symmetric failure)
and the failure surface(s) at both supports are relatively "clean" with a single surface failure
and the inclination of the failure surface(s) at both sides are relatively vertical
and inspection of the failure region indicates the main reinforcing bars have been mostly severed or sheared off

THEN:
damage level as determined by structural integrity analysis from visual information is total failure - Probability=1
and the mode(s) involved in the deformation process as determined by visual (subjective) information was predominantly direct shear - Probability=1
and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 3

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)
and the failure has occurred at the slab-wall connection
and the separated slab is lying flat on the floor (implying a symmetric failure)
and the failure surface(s) at both supports are relatively "clean" with a single surface failure
and the inclination of the failure surface(s) at both sides are relatively inclined or unclear
and inspection of the failure region indicates the main reinforcing bars exhibited rupture after significant deformation (note "necking" or stretching)

THEN:

damage level as determined by structural integrity analysis from visual information is total failure - Probability=1

and the mode(s) involved in the deformation process as determined by visual (subjective) information was predominantly diagonal tension - Probability=1

and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 4

IF:

complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)

and the failure has occurred at the slab-wall connection

and the separated slab is lying flat on the floor (implying a symmetric failure)

and the failure surface(s) at both supports are relatively rough with many cracks and "concrete teeth"

and the inclination of the failure surface(s) at both sides are relatively inclined or unclear

and inspection of the failure region indicates concrete crushed in the compression zone with possibly ripped out or protruding rebar

THEN:

damage level as determined by structural integrity analysis from visual information is total failure - Probability=1

and the mode(s) involved in the deformation process as determined by visual (subjective) information was predominantly shear-compression - Probability=1

and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 5

IF:

complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)

and the failure has occurred at the slab-wall connection

and the separated slab is lying flat on the floor (implying a symmetric failure)

and the failure surface(s) at both supports are relatively rough with many cracks and "concrete teeth"

and inspection of the failure region indicates the main reinforcing bars exhibited rupture after significant deformation (note "necking" or stretching)

THEN:

damage level as determined by structural integrity analysis from visual information is total failure - Probability=1

and the mode(s) involved in the deformation process as determined by visual (subjective) information were predominantly shear and diagonal tension,

causing rupture of reinforcement after significant rotation and deformation. It is possible that the failure region was underreinforced - Probability=1
and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 6

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)
and the failure has occurred at the slab-wall connection
and the separated slab is lying flat on the floor (implying a symmetric failure)
and the failure surface(s) at both supports are relatively rough with many cracks and "concrete teeth"
and inspection of the failure region indicates concrete crushed in the compression zone with possibly ripped out or protruding rebar
and the inclination of the failure surface(s) at NOT both sides are relatively inclined or unclear

THEN:
damage level as determined by structural integrity analysis from visual information is total failure - Probability=1
and the mode(s) involved in the deformation process as determined by visual (subjective) information were predominantly shear and diagonal tension, causing crushing of concrete after significant rotation. It is possible that the failure region was overreinforced or the concrete was weak in strength - Probability=1
and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 7

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)
and the failure has occurred well in the slab
and the separated slab is lying flat on the floor (implying a symmetric failure)
and the failure surface(s) at both supports are relatively "clean" with a single surface failure
and the inclination of the failure surface(s) at both sides are relatively inclined or unclear
and inspection of the failure region indicates the main reinforcing bars exhibited rupture after significant deformation (note "necking" or stretching)

THEN:
damage level as determined by structural integrity analysis from visual information is total failure - Probability=1

and the mode(s) involved in the deformation process as determined by visual (subjective) information was predominantly punching shear. This failure mode is slower than direct shear, where failure surfaces are vertical - Probability=1
and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 8

IF:
complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)
and the failure has occurred at the slab-wall connection
and the separated slab is leaning on/towards one side of the structure (implying an unsymmetrical failure)
and the failure surface(s) at one support is defined by a single surface failure which is relatively "clean", and the other is still partially attached or relatively "rough" with many cracks and "concrete teeth"
and the inclination of the failure surface(s) at one side is relatively vertical and the other side is relatively inclined or unclear

THEN:
damage level as determined by structural integrity analysis from visual information is total failure - Probability=1
and the mode(s) involved in the deformation process as determined by visual (subjective) information was predominantly direct shear, followed by concrete crushing and rebar pullout of the other side (possibly due to extremely high loading and/or weak concrete) - Probability=1
and [FAILURE MODES] IS GIVEN THE VALUE "KNOWN"

RULE NUMBER: 9

IF:
[FAILURE MODES] = "NOT KNOWN"
and complete failure of the structure is true (i.e., the roof slab has been completely separated from one or both of its supports)

THEN:
damage level as determined by structural integrity analysis from visual information is total failure - Probability=1
and the mode(s) involved in the deformation process as determined by visual (subjective) information is unknown due to insufficient or inadequate data - Probability=1

NOTE:
The information provided from the visual data was either inadequate or inconsistent with information contained in previous rules to determine a mode(s) of failure with any considerable amount of certainty.

RULE NUMBER: 10

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

THEN:

RUN(C:\DAPS\MAIN\FUZSET)

and the external program FUZSET.BAS has been run - Probability=1

NOTE:

The THEN portion of this rule simply calls an external program which asks questions of the user pertaining to the structural integrity of the structure, as ascertained from visual information.

RULE NUMBER: 11

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

THEN:

RUN(C:\DAPS\MAIN\COMBIN)

and the external program COMBIN.FOR has been run - Probability=1

NOTE:

The external program COMBIN.FOR uses fuzzy logic in the form of the DSW (Dong, Shah, Wong) algorithm to combine the linguistic information obtained from the user, with expert opinion relating this information to various modes of failure. The output is a group of 4 fuzzy sets relating the level of damage associated with a given mode.

RULE NUMBER: 12

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and the user would like to see the results of the DSW combination process just completed, i.e., the calculated (fuzzy set) levels of damage for each mode is : yes - please show them

THEN:

run(C:\DAPS\MAIN\COLORPLT)

and the external program PLOT.BAS has been run - Probability=1

NOTE:

Program COLORPLT.BAS takes the results of the DSW combination process obtained from the program COMBIN.FOR and simply plots the resulting fuzzy sets (damage level of a given mode).

RULE NUMBER: 13

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is none

THEN:

the damage to the structure associated with a shear response as determined by structural integrity analysis from visual information is none (i.e., no appreciable damage) - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 14

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is slight

THEN:

the damage to the structure associated with shear response as determined by structural integrity analysis from visual information is slight - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 15

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is moderate

THEN:

the damage to the structure associated with shear response as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 16

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is severe

THEN:

the damage to the structure associated with shear response as determined by structural integrity analysis from visual information is severe - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural intwgrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 17

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is very extensive

THEN:

the damage to the structure associated with shear response as determined by structural integrity analysis from visual information is very extensive - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 18

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and shear damage is unknown

THEN:
the damage to the structure associated with shear response as determined by structural integrity analysis from visual information is unknown - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 19

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and diagonal tension damage is none

THEN:
the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is none (i.e.,no appreciable damage) - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 20

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and diagonal tension damage is slight

THEN:

the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is slight - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 21

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and diagonal tension damage is moderate

THEN:

the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 22

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and diagonal tension damage is severe

THEN:

the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is severe - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 23

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and diagonal tension damage is very extensive

THEN:

the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is very extensive - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 24

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and diagonal tension damage is unknown

THEN:

the damage to the structure associated with diagonal tension response as determined by structural integrity analysis from visual information is unknown - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 25

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and flexure damage is none

THEN:
the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is none (i.e., no appreciable damage) - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 26

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and flexure damage is slight

THEN:
the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is slight - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 27

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and flexure damage is moderate

THEN:
the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 28

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and flexure damage is severe

THEN:

the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is severe - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 29

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and flexure damage is very extensive

THEN:

the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is very extensive - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 30

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and flexure damage is unknown

THEN:

the damage to the structure associated with a flexure response as determined by structural integrity analysis from visual information is unknown - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 31

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports) and tension membrane damage is none

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is none (i.e., no appreciable damage) - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 32

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and tension membrane damage is slight

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is slight - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 33

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and tension membrane damage is moderate

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 34

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and tension membrane damage is severe

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is severe - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 35

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and tension membrane damage is very extensive

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is very extensive - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 36

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and tension membrane damage is unknown

THEN:

the damage to the structure associated with tensile membrane response as determined by structural integrity analysis from visual information is unknown - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 37

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and overall damage is none

THEN:

the overall level of damage to the structure as determined by structural integrity analysis from visual information is none (i.e., no appreciable damage) - Probability=1

NOTE:

The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters. The overall damage is assumed to be

the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, tension membrane.

RULE NUMBER: 38

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and overall damage is slight

THEN:
the overall level of damage to the structure as determined by structural integrity analysis from visual information is slight - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

The overall damage is assumed to be the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, tension membrane.

RULE NUMBER: 39

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and overall damage is moderate

THEN:
the overall level of damage to the structure as determined by structural integrity analysis from visual information is moderate - Probability=1

NOTE:
The overall damage is assumed to be the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, and tension membrane. The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

RULE NUMBER: 40

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and overall damage is severe

THEN:
the overall level of damage to the structure as determined by structural integrity analysis from visual information is severe - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.
The overall damage is assumed to be the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, tension membrane.

RULE NUMBER: 41

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and overall damage is very extensive

THEN:
the overall level of damage to the structure as determined by structural integrity analysis from visual information is very extensive - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.
The overall damage is assumed to be the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, tension membrane.

RULE NUMBER: 42

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and overall damage is unknown

THEN:
the overall level of damage to the structure as determined by structural integrity analysis from visual information is unknown - Probability=1

NOTE:
The actual analysis procedure stated above is a fuzzy-weighted average algorithm implemented in a FORTRAN computer program. The damage levels

of the 10 structural integrity parameters supplied by the user are combined by weighting them with expert knowledge relating modes of failure to these same parameters.

The overall damage is assumed to be the largest damage level from each of the 4 modes - shear, flexure, diagonal tension, tension membrane.

RULE NUMBER: 43

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

THEN:

RUN(C:\DAPS\MAIN\TIM)

and the external program TIM.FOR has been run - Probability=1

NOTE:

Program TIM.FOR is used to calculate the early time response of the structure (i.e., at less than 2 ms) by using a modified Timoshenko beam analysis. Although the program is highly complex, the output is simple; early time response is categorized as either shear or flexure depending on which value reaches its critical failure level first.

RULE NUMBER: 44

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

THEN:

RUN(C:\DAPS\MAIN\IFPLOT)

and the external program IFPLOT.BAS has been run - Probability=1

NOTE:

Program IFPLOT.BAS is used to help determine the early time response of the structure (i.e., at less than 2 ms) by making a similarity comparison of pressure versus time plots at three locations of the roof slab. The three locations are near the wall, at the slab centerline, and over the wall. Similarity of different combinations of interface pressures at the roof/soil interface help determine modes of response.

RULE NUMBER: 45

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by modified Timoshenko beam analysis is shear

and early time response as determined by similarity analysis of interface
pressure plots is shear

THEN:

early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear - Probability=1

RULE NUMBER: 46

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by modified Timoshenko beam analysis is flexure

and early time response as determined by similarity analysis of interface pressure plots is flexure

THEN:

early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure - Probability=1

RULE NUMBER: 47

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by modified Timoshenko beam analysis is shear

and early time response as determined by similarity analysis of interface pressure plots is flexure or flexure-shear

THEN:

early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear - Probability=1

RULE NUMBER: 48

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by modified Timoshenko beam analysis is flexure

and early time response as determined by similarity analysis of interface pressure plots is flexure-shear

THEN:

early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear - Probability=1

RULE NUMBER: 49

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

THEN:

RUN(C:\DAPS\MAIN\DEFLECT)

and the external program DEFLECT.BAS has been run - Probability=1

NOTE:

Program DEFLECT.BAS shows the user the roof slab deflection profiles at 3 and 15 ms, and asks three questions of the user that are used in successive rules to help determine late time modes of response.

RULE NUMBER: 50

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small or small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late time response as determined by deflection profiles was predominantly shear - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 51

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small or small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

THEN:

late time response as determined by deflection profiles was initially shear, becoming substantial flexure as time progressed - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 52

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles was initially shear, but residual strength forced it into a tension membrane mode, possibly due to weak concrete - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 53

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late time response as determined by deflection profiles was predominantly shear - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 54

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

THEN:

late time response as determined by deflection profiles was a combination of shear and flexure - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 55

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles was substantial shear, followed by membrane response throughout - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 56

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is large

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late time response as determined by deflection profiles was almost exclusively shear - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 57

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is large

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

THEN:

late time response as determined by deflection profiles was mostly shear with some residual flexure response - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 58

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is large

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles was a combination of shear and tension membrane response (possibly due to weak concrete mix) - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 59

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface or a moderately curved surface

THEN:

late time response as determined by deflection profiles was predominantly flexure - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 60

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles is unknown because of inconsistent information and/or non-intuitive combination of antecedents - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 61

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small or small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late time response as determined by deflection profiles was a combination of shear and flexure - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 62

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

THEN:

late time response as determined by deflection profiles initiated as shear and/or diagonal tension, but flexure dominated thereafter - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 63

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles was predominantly tension membrane - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 64

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate or large

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

THEN:

late time response as determined by deflection profiles was predominantly shear (even though early response did not show overwhelming evidence of this) with some residual flexure - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 65

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

THEN:

late response as determined by deflection profiles was a combination of shear and flexure (even though early response did not show shear to be such a large factor) - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 66

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is moderate

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a highly curved surface

THEN:

late time response as determined by deflection profiles was initially shear (even though early response did not show overwhelming evidence of this fact) followed by extensive bending into membrane mode - Probability=1

and [LATE RESPONSE] IS GIVEN THE VALUE 1

RULE NUMBER: 67

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

and the difference between differential deflection ratios at the centerline and at a distance t = thickness from wall is small

THEN:

late time response as determined by deflection profiles was predominantly diagonal tension - Probability=1

and late time response as determined by deflection profiles was predominantly flexure - Probability=0

and [LATE RESPONSE] IS GIVEN THE VALUE 1

NOTE:

The second THEN statement is used to override a previous rule which would have found flexure to be dominant

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RULE NUMBER: 68

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

and the near wall deflection as determined by the external program DEFLECT.BAS is very small

and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a relatively flat surface

and the difference between differential deflection ratios at the centerline and at a distance t = thickness from wall is small

THEN:
late time response as determined by deflection profiles was predominantly diagonal tension - Probability=1
and late time response as determined by deflection profiles was predominantly flexure - Probability=0
and [LATE RESPONSE] IS GIVEN THE VALUE 1

NOTE:
The second THEN statement is used to override a previous rule which would have found flexure to be dominant.

RULE NUMBER: 69

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1
and the near wall deflection as determined by the external program DEFLECT.BAS is very small
and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface
and the difference between differential deflection ratios at the centerline and at a distance t = thickness from wall is small

THEN:
late time response as determined by deflection profiles was a combination of diagonal tension and flexure - Probability=1
and late time response as determined by deflection profiles was predominantly flexure - Probability=0
and [LATE RESPONSE] IS GIVEN THE VALUE 1

NOTE:
The second THEN statement is used to override a previous rule which would have found flexure to be dominant.

RULE NUMBER: 70

IF:
complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1
and the near wall deflection as determined by the external program DEFLECT.BAS is very small
and the ratio of differential deflection (near wall deflection minus centerline deflection) to slab thickness implies a moderately curved surface

and the difference between differential deflection ratios at the centerline and at a distance t = thickness from wall is small

THEN:

late time response as determined by deflection profiles was a combination of diagonal tension and flexure - Probability=1

and late time response as determined by deflection profiles was predominantly flexure - Probability=0

and [LATE RESPONSE] IS GIVEN THE VALUE 1

NOTE:

The second THEN statement is used to override a previous rule which would have found flexure to be dominant.

RULE NUMBER: 71

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and [LATE RESPONSE] = 0

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly shear = 1

THEN:

late time response as determined by deflection profiles is unknown because of inconsistent information and/or non-intuitive combination of antecedents - Probability=1

NOTE:

The most likely late time response was probably shear based on early time response.

RULE NUMBER: 72

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and [LATE RESPONSE] = 0

and early time response as determined by a combination of Timoshenko beam analysis and interface pressure data is predominantly flexure = 1

THEN:

late time response as determined by deflection profiles is unknown because of inconsistent information and/or non-intuitive combination of antecedents - Probability=1

NOTE:

The most likely late time response was probably flexure based on information from early time response.

RULE NUMBER: 73

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and [LATE RESPONSE] = 0
and early time response as determined by a combination of Timpshenko beam analysis and interface pressure data falls into the vague area of flexure-shear = 1

THEN:

late time response as determined by deflection profiles is unknown because of inconsistent information and/or non-intuitive combination of antecedents - Probability=1

NOTE:

A best guess of late time response would be a combination of flexure and shear based on early time response.

RULE NUMBER: 74

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and [DAMAGE LEVEL] < 0.2

THEN:

the overall damage to the structure as determined by deflection information is none - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR.

RULE NUMBER: 75

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)
and [DAMAGE LEVEL] > 0.20
and [DAMAGE LEVEL] < 0.40

THEN:

the overall damage to the structure as determined by deflection information is slight - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR.

RULE NUMBER: 76

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and [DAMAGE LEVEL] > 0.40

and [DAMAGE LEVEL] < 0.70

THEN:

the overall damage to the structure as determined by deflection information is moderate - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR.

RULE NUMBER: 77

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

and [DAMAGE LEVEL] > 0.7

and [DAMAGE LEVEL] < 1.0

THEN:

the overall damage to the structure as determined by deflection information is severe - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR.

RULE NUMBER: 78

IF:

complete failure of the structure is false (i.e., the roof slab has not been completely separated from one or both of its supports)

lnd [DAMAGE LEVEL] > 1.0

THEN:

the overall damage to the structure as determined by deflection information is very extensive - Probability=1

NOTE:

The value of the variable [DAMAGE LEVEL] is determined in the external program DEFLECT.FOR and returned via the program RETURN.FOR. The value of the variable is computed as the integral of the deflection (over the length of the slab) at 15 ms divided by length times thickness (to produce a dimensionless parameter).

LIST OF SYMBOLS

A_i = i^{th} structural attribute
B_1 = fuzzy set representation of no damage
B_2 = fuzzy set representation of slight damage
B_3 = fuzzy set representation of moderate damage
B_4 = fuzzy set representation of severe damage
B_5 = fuzzy set representation of very extensive damage
B_6 = fuzzy set representation of unknown damage
B' = fuzzy set representation of calculated damage level
BP = blast pressure gage
DOB = depth of burial
d = depth of concrete to principal tensile reinforcement
d' = depth of concrete to principal compressive reinforcement
E_{ij} = element of expert matrix [E]
EO = strain gage
$f_{c'}$ = compressive concrete strength
f_u = ultimate steel strength
f_y = steel yield strength
G = shear modulus
IF = interface pressure gage
L = roof slab clear span length
P = interface pressure
R = rotational end restraint of slab
r_{ij} = linguistic rating factor
S = horizontal distance between shear reinforcement
SE = soil strain gage
s = distance between shear reinforcement
t = slab thickness or time
U_j = element of user matrix [U]
w_j = linguistic weighting or importance factor
x_i = ith element of a set
α_i = value of i^{th} membership level
δ = deflection of roof slab
$\mu(x)$ = membership value of element x
ν = Poisson's ratio
ρ = percentage of principal tensile reinforcement
ρ' = percentage of principal compressive reinforcement
ρ_s = percentage of principal shear reinforcement
ϕ = internal angle of friction
Ω = strength enhancement factor